RECONSTRUCTION AND ANALYSIS OF CESIUM-137 FALLOUT DEPOSITION PATTERNS IN THE MARSHALL ISLANDS

By

ROBERT C. WHITCOMB, JR.

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Dedicated to
Mary, Christopher, & Taylor

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By

Robert C. Whitcomb, Jr.

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Chairman: W. Emmett Bolch, Jr.
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Estimates of ^{137}Cs deposition due to fallout originating from nuclear weapons testing in the Marshall Islands have been made for several locations in the Marshall Islands. These retrospective estimates were based primarily on historical exposure rate and gummed film measurements. The methods used to reconstruct these deposition estimates are specific for six of the Pacific tests. These methods are also similar to those used in the National Cancer Institute study for reconstructing ^{131}I deposition from the Nevada Test Site. Reconstructed cumulative deposition estimates are validated against contemporary measurements of ^{137}Cs concentration in soil. This validation work also includes an accounting for estimated global fallout contributions. These validations show that the overall geometric bias in predicted-to-observed (P/O) ratios is 1 .O (indicating excellent agreement). The 5th and 95th percentile range of this distribution is 0.35-2.95. The P/O ratios for estimates using historical gummed film measurements tend to slightly

over-predict more than estimates using exposure rate measurements. The methods produce reasonable estimates of deposition confirming that radioactive fallout occurred at atolls further south of the four northern atolls recognized by the Department of Energy as being affected by fallout. The deposition estimate methods, supported by the very good agreement between estimates and measurements, suggest that these methods can be used for other weapons testing fallout radionuclides with confidence.

CHAPTER 1
INTRODUCTION

This research and the author are supported by the Centers for Disease Control and Prevention (CDC). As such, this research will serve as a first step toward meeting CDC's eventual goal of performing a full thyroid dose reconstruction in the Marshall Islands. The research is intended to provide an evaluation of predictive methods for estimating ground deposition patterns of ^{137}Cs in the Marshall Islands. Once these methods have been developed and tested for ^{137}Cs, CDC will use these methods for other radionuclides (e.g., radioiodines).

The following sections present an overview of CDC's involvement including scientific and historical perspectives. Subsequent chapters introduce the deposition estimation methods, model validation, and uncertainty analysis used in this research. The chapters in this document and a brief description of how each are organized follows:

Chapter 1 (Introduction) provides a description of the Marshall Islands, a historical review of weapons testing in the Marshall Islands, and a brief overview of CDC's involvement and interest in the Marshall Islands. The goals and objectives of this study are also outlined and discussed.

Chapter 2 (Literature Review) provides a review of literature documenting related reconstructions done at other test sites. Specific literature includes reconstructions at the Nevada Test Site (NTS), the Utah Cohort Study, and Rongelap Atoll. Additional attention is given to the Health Physics Journal Special Issue on the Marshall Islands.

Chapter 3 (Methods) introduces the methods used in this research. Methods to estimate the deposition of Cesium-137 (^{137}Cs) are discussed, followed by a description of how uncertainty is accounted for in the estimates.

Chapter 4 (Data) introduces the input data and validation data sets used in this research. Input data consist of historical monitoring data collected by various organizations. Validation data sets come from contemporary measurements of ^{137}Cs in soil.

Chapter 5 (Calculations and Assumptions) introduces the calculations performed with the input of historical monitoring data. All data (with associated and derived uncertainties) used by the model are discussed. Finally, a Monte Carlo uncertainty analysis and a qualitative sensitivity analysis are used to assess the relative importance of different variables on the model's predictions.

Chapter 6 (Model Validation) presents the validation procedures and results for several Atolls in the Marshall Islands. The model validation output includes ratios of predictions to observations (P/O) and a discussion of model bias.

Chapter 7 (Results and Conclusions) discusses the model's outputs for estimating the deposition of ^{137}Cs in the Marshall Islands. Information regarding the predictive capability (method bias) of the methods is included. Recommendations and conclusions based on these outputs are also provided.

A glossary is provided at the end of Chapter 7. This glossary provides descriptions of acronyms and terms used in this thesis. Many of these acronyms and terms are no longer used in contemporary publications, but are defined in this work due to the use of historical documents in this research.

Purpose of this Study

The purpose of this study is to develop computerized methods to reconstruct the deposition of ^{137}Cs in the Marshall Islands. Beyond this primary purpose, this research will test the method predictions against environmental data and determine which atolls exhibit ^{137}Cs contamination in soil above the global fallout estimates.

Background Information

The Marshall Islands have a long history of visitation and occupation by foreign countries. Germany was the first foreign power to control the atolls in the late 19th century. From 1914 through World War II, Japan occupied and controlled the atolls. Following World War II, the Marshall Islands became a United Nations Trust Territory under United States trusteeship. During this time, the Marshall Islands were selected as a site for U.S. nuclear weapons tests. In 1982, the Republic of the Marshall Islands (RMI) became an independent nation.

Description of the Marshall Islands

Geography. The Marshall Islands is a group of 29 atolls and five separate reef islands in the Pacific Ocean, approximately 3,220 kilometers (2,000 miles) southwest of Hawaii and 3,700 kilometers (2,300 miles) southeast of Tokyo. A map of the islands is shown in Figure 1 - 1 (adapted from Musolino et al. 1997). The islands are located between 4 and 14 degrees North latitude and 160 and 173 degrees East longitude. The atolls consist of two somewhat parallel island chains; the Ratak (sunrise) chain and Ralik (sunset) chain. These chains are comprised of 1,255 islets scattered over a geographical area of approximately 1,944,000 square kilometers (750,000 square miles) but with a land area of less than 18 1 square kilometers (70 square miles). (RMI 1990)

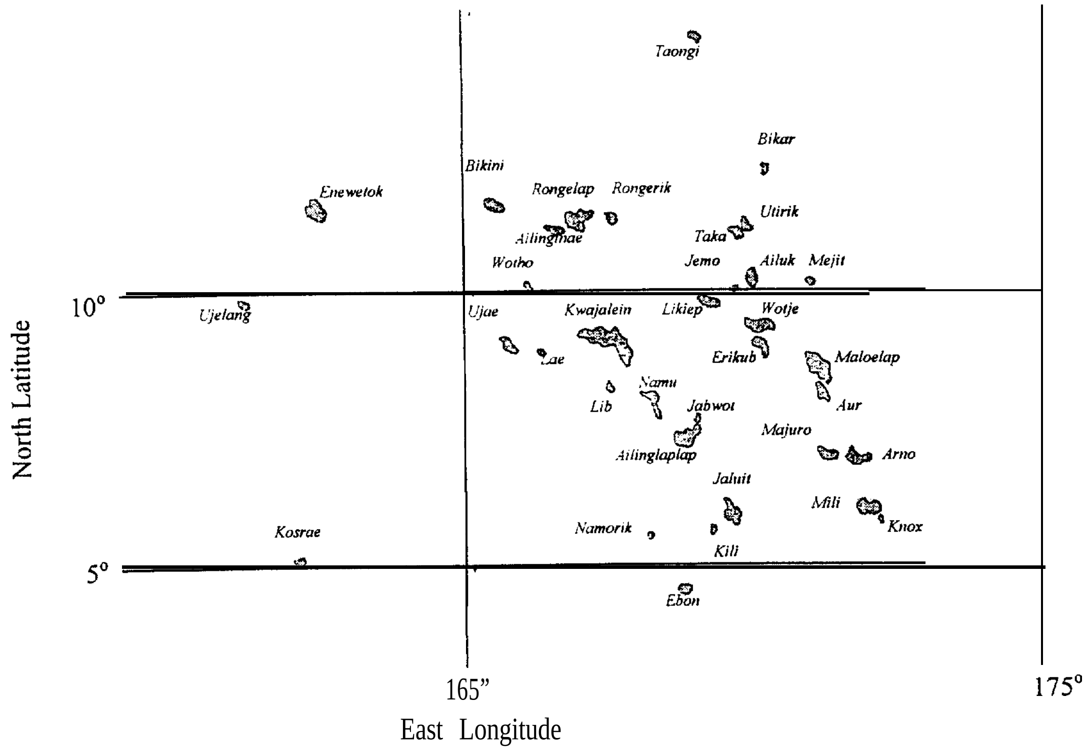

Figure l-l Map of the Republic of the Marshall Islands.

<u>Climate.</u> The climate of the Marshall Islands is hot and humid due to its proximity to the equator. Average temperature is about 27 degrees Celsius (81° F) with an average relative humidity of 8 1% in Majuro. Rainfall is greater in the southern atolls than the northern atolls. October and November are the wettest months of the year. Average annual rainfall in Majuro is 335 cm (132 inches). Although Typhoons are rare for the Marshall Islands, they do border the area of the pacific known as the “typhoon belt.” Prevailing winds (or “Trade Winds”) are from the Southwest to the Northeast (Donaldson et al. 1997).

Terrain. The Atolls are composed of low coral limestone deposits and sand islands. Elevations range from zero to ten meters above mean sea level. Vegetation is generally low-lying except for coconut groves used for copra production.

Population. The total population of the RMI is currently estimated (1995 estimate based on projections of 1988 census) to be about 56,000 people (RMI 1988). About two thirds of the population currently live on the urbanized atolls of Majuro and Kwajalein. Historically the population was more evenly distributed across all of the atolls.

History of Testing in the Marshall Islands

Between 1946 and 1958, the United States conducted 66 nuclear weapons tests in the Marshall Islands. The rests were conducted on the northwestern atolls of Bikini and Enewetak. Twenty-three of the tests were conducted at Bikini and the remaining 43 were conducted at Enewetak. Although the period of testing spans 12 years, the tests were done in series that occurred mostly during even years and lasted two to three months. Table l-l shows test date. location, yield, type and configuration for the 66 tests (DOE 1994).

One other test was conducted during Operation Hardtack I. This test, named Yucca, occurred on 4/28 58 at 2:40 PM. The test yield was 1.7 ktons detonated from a balloon about 15 7 km (85 nrni) northeast of Enewetak. The height of detonation was approximately 26.2 km (86.000 feet).

Castle Bravo

On March 1, 1954. the Castle Bravo test at Bikini Atoll heavily exposed Marshall Islanders on Ronpelap. Ailinginae, and Utirik Atoll to radioactive fallout. The people were eventually evacuated from their home islands. Estimates of whole body and thyroid doses on Rongelap from the Bravo test were 1.9 Gy (190 rad) and 20 Gy (2000 rad), respectively (Lessard et al. 1985).

Table 1 - 1 Nuclear Weapons Tests Conducted in the Marshall Islands.

Test	Operation	Local Date”	Local Time[b]	Total Yield, kTons	Atoll	Type
Able	Crossroads	7/1/46	9:00 AM	21	Bikini	Airdrop
Baker	Crossroads	7/25/46	8:35 AM	21	Bikini	Underwater
X-ray	Sandstone	4/15/48	6:17 AM	37	Enewetak	Tower
Yoke	Sandstone	5/1/48	6:09 AM	49	Enewetak	Tower
Zebra	Sandstone	5/15/48	6:04 AM	18	Enewetak	Tower
Dog	Greenhouse	4/8/51	6:34 AM	81	Enewetak	Tower
Easy	Greenhouse	4/21/51	6:27 AM	47	Enewetak	Tower
George	Greenhouse	5/9/51	9:30 AM	225	Enewetak	Tower
Item	Greenhouse	5/25/51	6:17 AM	45.5	Enewetak	Tower
Mike	Ivy	11/1/52	7:14 AM	10400	Enewetak	Surface
King	Ivy	11/16/52	11:30 AM	500	Enewetak	Airdrop
Bravo	Castle	3/1/54	6:45 AM	15000	Bikini	Surface
Romeo	Castle	3/27/54	6:30 AM	11000	Bikini	Barge
Koon	Castle	4/7/54	6:20 AM	110	Bikini	Surface
Union	Castle	4/26/54	6: 10 AM	6900	Bikini	Barge
Yankee	Castle	5/5/54	6: IO AM	13500	Bikini	Barge
Nectar	Castle	5/14/54	6:20 AM	1690	Enewetak	Barge
Lacrosse	Redwing	5/5/56	6:25 AM	40	Enewetak	Surface
Cherokee	Redwing	5/21/56	6:00 AM	3800	Bikini	Airdrop
Zuni	Redwing	5/28/56	5:56 AM	3530	Bikini	Surface
Yuma	Redwing	5/28/56	7:56 AM	0.19	Enewetak	Tower
Erie	Redwing	5/31/56	6:15 AM	14.9	Enewetak	Tower
Seminole	Redwing	6/7/56	12:55 PM	13.7	Enewetak	Surface
Flathead	Redwing	6/12/56	6:26 AM	365	Bikini	Barge
Blackfoot	Redwing	6/12/56	6:26 AM	8	Enewetak	Tower
Kickapoo	Redwing	6/14/56	11:26 AM	1.49	Enewetak	Tower
Osage	Redwing	6/17/56	1:14 PM	1.7	Enewetak	Airdrop
Inca	Redwing	6/22/56	9:26 AM	15.2	Enewetak	Tower
Dakota	Redwing	6/26/56	6:06 AM	1100	Bikini	Barge
Mohawk	Redwing	7/3/56	6:06 AM	360	Enewetak	Tower
Apache	Redwing	7/9/56	6:06 AM	1850	Enewetak	Barge
Navajo	Redwing	7/1 1/56	5:56 AM	4500	Bikini	Barge
Tewa	Redwing	7/21/56	5:00 AM	5000	Bikini	Barge
Huron	Redwing	7/22/56	6:12 AM	250	Enewetak	Barge
Cactus	Hardtack I	5/6/58	6: 15 AM	18	Enewetak	Surface

Table l-l - - continued.

Test	Operation	Local Date”	Local Time[b]	Total Yield, kTons	Atoll	Type
Fir	Hardtack I	5/12/58	5:50 AM	1360	Bikini	Barge
Butternut	Hardtack I	5112158	6:15 AM	81	Enewetak	Barge
Koa	Hardtack I	5/13/58	6:30 AM	1370	Enewetak	Surface
Wahoo	Hardtack I	5/17/58	1:30 PM	9	Enewetak	Underwater
Holly	Hardtack I	5/21/58	6:30 AM	5.9	Enewetak	Barge
Nutmeg	Hardtack I	5/22/58	9:20 AM	25.1	Bikini	Barge
Yellowwood	Hardtack I	5/27/58	2:00 PM	330	Enewetak	Barge
Magnolia	Hardtack I	5/27/58	6:00 AM	57	Enewetak	Barge
Tobacco	Hardtack I	5/31/58	2:15 PM	11.6	Enewetak	Barge
Sycamore	Hardtack I	6/1/58	3:00 PM	92	Bikini	Barge
Rose	Hardtack I	6/3/58	6:45 AM	15	Enewetak	Barge
Umbrella	Hardtack I	6/9/58	11:15 AM	8	Enewetak	Underwater
Maple	Hardtack I	6/1 1/58	5:30 AM	213	Bikini	Barge
Aspen	Hardtack I	6/15/58	5:30 AM	319	Bikini	Barge
Walnut	Hardtack I	6/15/58	6:30 AM	1450	Enewetak	Barge
Linden	Hardtack I	6/19/58	3:00 PM	11	Enewetak	Barge
Redwood	Hardtack I	6/28/58	5:30 AM	412	Bikini	Barge
Elder	Hardtack I	6/28/58	6:30 AM	880	Enewetak	Barge
Oak	Hardtack I	6/29/58	7:30 Aii	8900	Enewetak	Barge
Hickory	Hardtack I	6/30/58	12:OO PM	14	Bikini	Barge
Sequoia	Hardtack I	7/2/58	6:30 AM	5.2	Enewetak	Barge
Cedar	Hardtack I	7/3/58	5:30 AM	220	Bikini	Barge
Dogwood	Hardtack I	7/6/58	6:30 Aii	397	Enewetak	Barge
Poplar	Hardtack I	7/13/58	3:30 PM	9300	Bikini	Barge
Scaevola[c]	Hardtack I	7/15/58	4:00 P M	0.0	Enewetak	Barge
Pisonia	Hardtack I	7/18/58	11:00 AM	255	Enewetak	Barge
Juniper	Hardtack I	7/23/58	4:20 PM	65	Bikini	Barge
Olive	Hardtack I	7/23/58	8:30 AM	202	Enewetak	Barge
Pine	Hardtack I	7/27/58	8:30 AM	2000	Enewetak	Barge
Quince[d]	Hardtack I	8/7/58	2:15 PM	0.0	Enewetak	Surface
Fig	Hardtack I	8/19/58	4:00 PM	0.02	Enewetak	Surface

[a] Date is local date converted from Greenwich Civil Time (GCT)

[b] Reference: DNA (1982a, 1982b. 1982c, 1982d, 1983a, 1983b, 1984)

[c] Safety experiment

[d] Weapons related, yield was not up to expectation

Brookhaven National Laboratory (BNL) scientists have observed thyroid disease in the Marshall Islands population (Conard et al. 1974). Their study showed an increase in various thyroid neoplasia and other types of thyroid disease (hypothyroidism, thyroid nodules and thyroid carcinoma) to those with estimated exposures. The incidence of thyroid cancer among the highly exposed group was estimated at 7%. The cumulative incidence of thyroid nodular abnormalities among the highly exposed group was estimated to be 22%.

In addition to BNL's observance of thyroid disease, Hamilton (et al. 1987) noted an inverse relationship between prevalence of thyroid disease and distance from the Bikini test site. His work showed thyroid nodularity ranged from 10% in Utirik to 1% in Mili Atoll with many midbelt atolls falling between 5 and 10%.

Until recently, Hamilton's findings were the only hint that other atolls may have received fallout from the testing. Newly discovered information shows evidence of potential widespread fallout contamination throughout the Marshall Islands,

CDC Interest

The CDC. in collaboration with the RMI Ministry of Health and Environment (MOHE) has proposed conducting a Nationwide Thyroid Disease Study for the Marshall Islands (CDC. 1998). The purpose of the proposed study will be to:

1. Determine the occurrence of thyroid neoplasms in current RMI residents who lived in the RMI and were younger than 15 years of age during the years of US atomic weapons testing, 1946-1958;
2. Estimate thyroid radiation doses for these persons; and
3. Determine if there is an epidemiologic association between the occurrence of thyroid neoplasms and radiation exposures.

There are many scientific and historical considerations that make this proposed study challenging and unique. These considerations are presented in the following perspectives.

Scientific Perspectives

The Marshall Islands has one of the few populations exposed to environmental radiation where there is evidence of a high prevalence of thyroid abnormalities. The type of exposure experienced by this population is very different from that experienced by other populations:

1. Health effects from atomic weapons have primarily been studied for instantaneous exposure (e.g., Hiroshima and Nagasaki). In the RMI, 66 tests were conducted over a period of 12 years;
2. Fallout radionuclide composition was different and more diverse than other episodic exposures, such as those from accidental or planned releases from plants in the US involved in the production of nuclear weapons; and
3. Exposure pathways in the RMI are very different from those of any previously studied radiation contamination incident (e.g., there is no milk pathway for the RMI population).

Historical Perspectives

The United States conducted a variety of nuclear weapons tests in the Marshall Islands between 1946 and 1958, which resulted in documented radioactive contamination of a number of atolls. The US Government has supported ongoing radiation monitoring and medical examinations for Rongelap residents exposed to fallout from the nuclear test Bravo. This population has a high rate of thyroid disease from this exposure.

The US Government has maintained that other populations in the Marshall Islands did not receive significant fallout exposures or have any adverse radiation-related health effects. However, the RMI Government has had continuing concerns that radiation contamination and related health effects are more widespread in the RMI than radiation scientists have reported. To assess present day contamination levels, the RMI began a Nationwide Radiological Survey (NWRS) in 1989, led by Dr. Steven Simon. This survey measured gamma radiation levels and ^{137}Cs concentrations in soil profile samples collected from all atolls (Simon and Graham, 1997). A retrospective dose assessment for the entire population of the RMI was planned as part of the NWRS, but to date has not been carried out.

In 1993 the RMI MOHE requested CDC assistance in conducting a nationwide thyroid disease study. The MOHE wished to assess the distribution of thyroid neoplasms and historical radiation exposures throughout the RMI, and to determine whether there was an epidemiologic link between thyroid disease and radiation exposure. The proposed CDC thyroid study would provide estimates of historic thyroid doses, and would help determine the need to conduct further dose assessments for the entire RMI population.

Congress has directed CDC to conduct studies of thyroid disease in Utah residents resulting from radiation exposures from weapons testing done at the NTS. Historical documents available for the Marshall Islands testing program suggest that potential radiation exposures from weapons testing done in the RMI may be much larger than those estimated for Utah residents for whom Congress has mandated health studies.

The National Academy of Sciences (NAS) reviewed a draft protocol for this proposed study in December 1995. An ad-hoc peer review panel reviewed a revised draft protocol in September 1998. The NAS and ad-hoc peer reviewers recommended that CDC develop more information on radiation exposure prior to conducting the epidemiologic study. The research conducted and described in this work is the first step toward meeting the recommendations of the peer reviews.

Goals and Objectives

The purpose of this study is to develop and test computerized methods to estimate the deposition of ^{137}Cs in the Marshall Islands. These computerized methods employ the use of commercially available spreadsheet and forecasting software (e.g., Microsoft Excel and Crystal Ball). Once these methods have been developed and tested for ^{137}Cs, CDC will use these methods for other radionuclides (e.g., radioiodines). Beyond this primary goal, this research will:

1. Evaluate historical and contemporary measurement data;
2. Reconstruct the levels of ^{137}Cs fallout deposition on selected mid-belt atolls using historical measurement data;
3. Compare the reconstructed levels with the global contribution; and
4. Validate these reconstructed levels with contemporary soil measurements.

CHAPTER 2
LITERATURE REVIEW

Introduction

This chapter discusses other related retrospective studies and sources of information used in or related to this research. The methodology used in this research builds on methods developed for the Nevada Test Site (NTS) and Utah Cohort Study dose reconstructions. This is the first use of these methods in the Republic of the Marshall Islands (RMI).

Retrospective Studies in the U.S.

Other dose reconstruction efforts have been conducted in the United States. These efforts include the NTS Study and the Utah Cohort Study. A review of these studies and their similarity to this research is described below.

Nevada Test Site

The National Cancer Institute (NCI) reconstructed exposures and thyroid dose estimates to the 48 contiguous states of the United States population from ^{131}I following atmospheric tests in Nevada (NCI 1997). This study, initiated by Public Law 97-4 14 (USHR 1983), directed the Secretary of Health and Human Services to

> "conduct scientific research and prepare analyses necessary to develop valid and credible methods to estimate the thyroid doses of Iodine-l 3 1 that are received by individuals from nuclear bomb fallout (and) to develop valid and credible assessments of the exposure to Iodine-13 1 that the American people received from the Nevada atmospheric nuclear bomb tests.. ."

The NCI report includes radioiodine deposition estimates by county for the entire continental United States. From this deposition pattern, estimates are derived of cumulative average thyroid dose by age, gender and source of milk consumption. The major pathway contributing to thyroid dose was the transport of radioiodine to individuals through milk consumption.

Utah

The University of Utah conducted a cohort study of thyroid disease in Utah with support from the NCI (Utah 1992). This study used similar methods and built upon radioiodine fallout patterns developed for the NTS Study. The study was undertaken to:

1. locate living members of the original thyroid study cohort in Utah, Nevada, and Arizona for re-examination and to interview their parents;
2. assign each member an estimated individual thyroid dose; and
3. determine if there is a relationship between thyroid dose and disease.

As with the NTS study, the major pathway of concern was the transport of radioiodine to individuals through milk consumption.

Retrospective Studies in the Marshall Islands

Other limited dose reconstruction efforts using different methodologies have been conducted in the Marshall Islands. Cumulative external exposure estimates for the Marshall Islanders were first estimated following the Bravo test. Internal thyroid dose estimates were later reconstructed for the people of Rongelap, Ailinginae, and Utirik (Cronkite et al. 1956; James 1964; Conard et al. 1974). More recently, Brookhaven National Laboratory (BNL) scientists reconstructed thyroid dose for people at Rongelap, Utirik, and Sifo resulting from the March 1, 1954 Bravo detonation (Lessard, et al. 1985).

The latest effort was a reconstruction of thyroid dose estimates to several atolls further away from Rongelap (Musolino 1997). Musolino extended the thyroid dose estimates resulting from Bravo to Ailuk, Likiep, Jemo, Mejit, Wotho, Wotje, Lae, and Ujae Atolls. None of these studies used the same methodology developed for the NTS.

External Dose Reconstructions.

Because of the high level of exposure received by the populations of the northern atolls from the Bravo test, previous exposure assessments in the Marshall Islands have focused on doses to these populations from the Bravo test or the entire Castle Series. Breslin and Cassidy (1955) first published estimates of the external whole body exposures from the Castle Series. These investigators analyzed data from aerial and ground surveys collected by the Atomic Energy Commission (AEC). They estimated finite external exposures (defined as the cumulative exposure from the detonation of a particular test up until the time of the next test) for each atoll and from each test within the series. As shown in Table 2- 1, these estimates vary between individual tests and between atolls. This variation in the distribution of fallout was a function of the size of the weapon being tested, as well as the wind direction and other meteorological conditions existing at the time of the individual test. The last column is a summation across rows. However, the actual line totals differ from the reference table. This discrepancy may be due to rounding and/or calculation errors. For example, the sum for Lae Atoll is 210 mR instead of the 125 mR listed in Table 2-l taken from the original reference.

Table 2-l Operation Castle Cumulative Exposures (mR) by Event and Location.

Atoll&land	Bravo	Romeo	Koon	Union	Yankee	Nectar	Total
Ailinginae	60000	3400	3300	8	600	70	67000
Ailinglaplap	7.2	140	100	8	0	0	255
Ailuk	5000	410	110	100	500	20	6140
Amo	60	200	300	8	25	1.3	594
Aur	40	200	50	8	40	2.6	341
Bikar	60000	3000	1200	650	1700	150	67000
Ebon	20	250	50	8	25	0	353
Erikub	390	200	50	0	0	6.5	647
Jaluit	20	300	70	8	0	2.6	401
Jemo	1200	410	130	18	200	20	1978
Kili	20	200	70	0	0	1.3	291
Kwajalein	150	480	250	12	320	17	1235
Lae	5.5	12	12	7.5	78	95	125
Likiep	1700	170	80	30	200	16	2196
Maj uro	200	200	50	20	0	1.3	471
Maloelap	350	120	50	0	25	4	549
Mili	60	160	200	20	0	1.3	441
Namorik	20	160	70	2	0	0	252
Namu	1.8	90	100	0	25	0	216
Rongelap	180000	11000	6000	3400	1700	300	202000
Rongerik	190000	9000	5000	550	1400	280	206000
Taka	15000	800	1000	120	380	50	17000
Taongi	280	60	9.5	10	10	- -[a]	370
Ujae	6	32	17	9.5	48	1.4	114
Ujelang	85.4	- -[a]	176	52	142	- -[a]	455
Utirik	22000	1200	700	100	330	50	24000
Wotho	250	270	110	55	95	4	784
Wotje	1800	300	200	13	220	10	2543

[a] no estimate given.

Although Bravo had the highest yield of any test in the Castle series, the fallout (as represented by exposure levels) from subsequent tests was also significant particularly in the northern atolls. However, population doses from these later tests were significantly lower than those received from Bravo because of the evacuation of the Marshallese people from the northern atolls of Rongelap and Ctirik after the Bravo test. As illustrated by the lines of equivalent integrated exposure in Figure 2-1, cumulative whole-body exposures from the Castle series were highest directly to the east of Bikini, were elevated to the south, and declined with distance. Thyroid doses at a given location would have been higher than the estimated external whole body exposure because of the intake and concentration of radioiodines in the thyroid (Lessard 1985; Musolino et al. 1997).

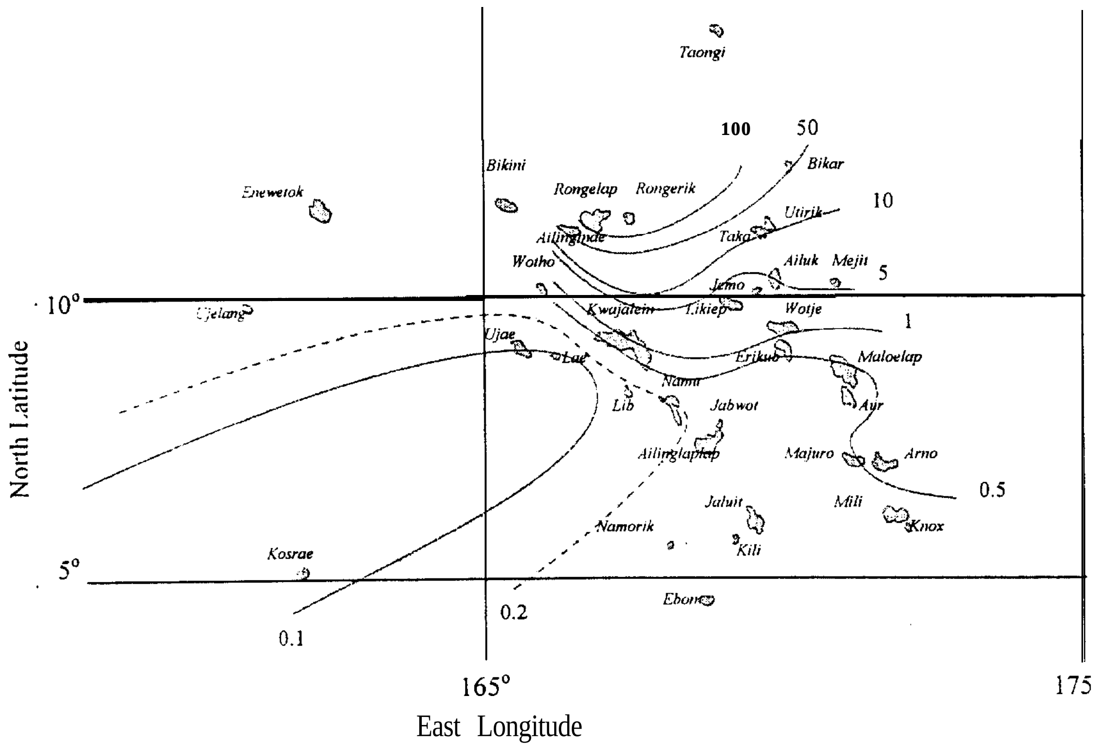

Figure 2-1 Integrated External Exposures (R) in the Marshall Islands Resulting from Operation Castle.

The Public Health Service (PHS) estimated cumulative external whole body exposures from rhe Redwing and Hardtack I Series for Wotho, Rongelap, Ujelang, Utirik and Rongerik atolls. PHS personnel conducted ground level surveys and operated fixed-instrument locations during testing in the Marshall Islands (PHS 1958; PHS 1954). These estimates. provided in Table 2-2, were derived using measurements of exposure

($mR\ hr^{-1}$) from survey meters and cumulative exposure (mR) from film badges. These data indicate that fallout from tests other than those in the Castle Series reached the populated atolls of Wotho and Ujelang. As with the Castle series: the thyroid doses to individuals at these locations from Operation Redwing and Hardtack are expected to have been higher than the external whole body exposures.

Table 2-2 Cumulative External Exposure (mR) Estimates for Three Test Series.

Location	Test Series: Castle	Redwing	Hardtack I
Wotho	784	616	142
Rongerik	206,000	853	---[a]
Rongelap	202,000	---[a]	285
Uj elang	455	560	222
Utirik	24,000	53	230

[a] no measurements taken during this series
Source: Breslin and Cassidy 1955; PHS 1958; PHS 1954

<u>Internal Dose Reconstructions.</u>

Radioisotopes of iodine (both short and long-lived) are a significant product of nuclear fission. Because the thyroid concentrates iodine and is particularly sensitive to the carcinogenic properties of radiation, doses to the thyroid of individuals exposed to weapons fallout are of particular concern. Thyroid dose estimates for the people of Rongelap, Ailinginae, and Utirik have been prepared by a number of researchers since the Bravo test (Cronkite et al. 1956; James 1964; Conard et al. 1974, Lessard et al. 1985).

The original estimate of thyroid doses for the people of Rongelap was 100 to 150 rep (Cronkite et al. 1956). This is an outdated unit of absorbed dose where 1 rep = 0.93 rad (0.0093 Gy or 9.3 mGy) for soft tissue. Therefore, the original estimate was somewhere between 0.93 and 1.4 Gy (93 and 140 rad) to the thyroid.

Later, in 1964, investigators at the Lawrence Radiation Laboratory estimated that the total thyroid absorbed dose to the child was two to five times higher than Cronkite's original estimate for the Rongelap people (James 1964). These estimates were extrapolated to other atolls and age groups by Conard in 1974 (Conard et al. 1974).

However, updated thyroid dose estimates developed by Brookhaven National Laboratory (BNL) are the most detailed. BNL re-evaluated urine bioassay data and archived soil samples collected after the Castle Bravo incident (Lessard et al. 1985). In addition, they developed new estimates of the quantity of radiation in the fallout cloud and modeled the effects of meteorology and other factors on the Bravo fallout. Their assessment included doses for 10 age- and gender-specific categories for populations on Rongelap and Utirik Atolls, and Sifo Island, Ailinginae Atoll, and included in utero doses. External and internal contributions to thyroid dose were reported, as well as total absorbed dose to the thyroid. A summary of these dose estimates is provided in Table 2-3. As shown in the table, internal radioiodines were by far the largest contributor to the total thyroid dose. Moreover. while external contributions to atoll-specific thyroid absorbed dose remained consistent across age and gender categories, internal dose estimates were two to five times higher in children (through age 14) than for adults.

Most recently, Musolino et al. (1997) reconstructed thyroid absorbed doses for eight inhabited atolls south of Bikini and north of Kwajalein. The atolls for which doses were estimated are located in the middle or "mid-belt" atolls of the Marshall Islands. Estimates were not provided for the southern-most atolls. Musolino et al. (1997) reconstructed doses primarily from external exposure data compiled for the Castle series by Breslin and Cassidy (1955). Thyroid doses were estimated for adult males and

Table 2-3 Thyroid Absorbed Dose (rad) for Individuals of Rongelap, Utirik, and Sifo Resulting from the Bravo Test.

Atoll	Individual	Internal	External	Total
Rongelap	Adult Male	1000	190	1190
	Adult Female	1100	190	1290
	Fourteen-year-old	1400	190	1590
	Twelve-year-old	1600	190	1790
	Nine-year-old	2000	190	2190
	Six-year-old	2400	190	2590
	One-year-old	5000	190	5190
	Newborn	250	190	440
	In Utero, 3rd trimester	680	190	870
	In Utero, 2nd trimester			0
Ailinginae, Sifo	Adult Male	280	110	390
	Adult Female	290	110	400
	Fourteen-year-old	410	110	520
	Twelve-year-old	450	110	560
	Nine-year-old	540	110	650
	Six-year-old	640	110	750
	One-year-old	1300	110	1410
	Newborn		110	110
	In Utero, 3rd trimester		110	110
	In Utero, 2nd trimester	490	110	600
Utirik	Adult Male	150	11	161
	Adult Female	160	11	171
	Fourteen-year-old	220	11	231
	Twelve-year-old	240	11	251
	Nine-year-old	300	11	311
	Six-year-old	340	11	351
	One-year-old	670	11	681
	Newborn	48	11	59
	In Utero, 3rd trimester	98	11	109
	In Utero, 2nd trimester	260	11	271

Source: Lessard et al. 1985

females and for a one-year-old child. Estimated thyroid doses and the whole body external exposures on which the estimates are based are provided for a one-year-old child in Table 2-4. Thyroid doses for a one-year-old child range from 0.01 Gy (1 rad) at Lae atoll to 2.25 Gy (225 rad) at Ailuk atoll. Based on their findings, Musolino et al. (1997)

recommended that a systematic medical survey for thyroid disease and a more definitive dose reconstruction be carried out for all of the populated atolls and islands in the northern Marshall Islands.

Table 2-4 Estimated One-Year-Old Child Thyroid Absorbed Dose Resulting from the Bravo Test.

Location	Thyroid Dose, rad
Ailuk	225
Likiep	81
Jemo	72
wotho	34
Wotje	72

Source: Musolino et al. 1997

Journal of the Health Physics Society Special Issue on the Marshall Islands

In July 1997, the Health Physics Journal published a special issue entitled, "Consequences of Nuclear Testing in the Marshall Islands." This special issue included papers from a variety of scientists and organizations involved in the past or with continuing involvement in the Marshall Islands. The issue was divided into the following sections: a) History, bj Radiological Monitoring, c) Dose Assessment, d) Health Effects. e) Environmental Studies, and f) Additional Papers.

The special issue presented a good historical and contemporary overview of testing and subsequent health effects studies performed in the Marshall Islands. However, this special issue lacked an article on a comprehensive dose reconstruction for the entire Marshall Islands. Musolino (1997), in a later issue of the Health Physics Journal, called for this type of dose reconstruction to be performed.

Document Repositories

This section describes the document repositories holding and supplying useful data. Several document sources and repositories were used in obtaining the relevant information for this research. The first source included more than 30 boxes of documents that were released by DOE to the RMI. Other documents were obtained from the following repository sites:

1. Brookhaven National Laboratory, Upton, NY;
2. Coordination and Information Center facilities in Las Vegas, NV;
3. Naval records repository in San Bruno. CA;
4. Department of Defense Nuclear Information Analysis Center in Albuquerque, NM;
5. Environmental Measurements Laboratory (EML), Department of Energy, New York. NY; and
6. Lawrence Livermore National Laboratory, Livermore, CA.

The document repository that contains the most relevant documents is the Coordination and Information Center (CIC) in Las Vegas. Nevada. The CIC was established by the Off-Site Radiation Exposure Review Project (ORERP) as a public collection of historical information relating to environmental fallout from the NTS. More than 400,000 documents are included or identified for inclusion in this repository. Document information is entered in a bibliographic database that is searchable from the Department of Energy's OpenNet web site. Although the primary focus of the CIC records holdings is related to fallout from the NTS, many documents relating to the Pacific Proving Ground (PPG) are also contained here.

Information obtained from these sources include individual shot fission yield, fractionation data, meteorological observations, particle size distributions with distance, plume time of arrival at each atoll, exposure rate measurements from aerial and ground surveys, fallout patterns from gummed film, and historical radioactivity measurements on a variety of environmental media. Chapter 4 describes in more detail the data obtained from the various document repositories.

CHAPTER 3
METHODS

Introduction

This chapter discusses the methods and formulas used in this research. These methods are similar to those employed to reconstruct production, deposition, and dose from weapons testing at other test sites. The proven method is one used in the Nevada Test Site (NTS) Offsite Environmental Dose Reconstruction Project (HPS 1990). This methodology employs the use of normalized deposition factors from various measurements of fallout and exposure rates in the environment as described by Hicks (1982). Although most data tables developed by Hicks are specific to the NTS, other work by Hicks (1984) is specific to the Marshall Islands. Simon (1996) suggested that these methods be used for retrospective dose assessments in the Republic of the Marshall Islands (RMI).

Estimating ^{137}Cs Production

The method for estimating ^{137}Cs production from nuclear weapons testing is described in this section. The amount of each radionuclide produced is dependent on the type and composition of the nuclear device. How much is released to the atmosphere is dependent on the size and location of the detonation. For example, nuclear devices may be fission only or a combination of the fission and fusion process. The amount of fission products (e.g. ^{137}Cs) produced is dependent on how much of the device yield is due to fission Devices that rely on the fission-fusion process are known as thermonuclear devices.

The amounts of radionuclides produced by the testing in the Marshall Islands can be estimated with the following equation derived for this study:

$$P_r = Y_d \cdot F_f \cdot Y_r$$

where

P_r = Production of radionuclide r, Mega (Million) Curies;

Y_d = Yield of device, Mton;

F_f = Fraction of yield due to fission (i.e.,. fission yield/total yield); and

Y_r = yield of radionuclide r, MCi $Mton^{-1}$.

The first parameter needed for the equation is the total yield (Y_d) for the device or series. Values for this parameter are the sum of individual test yields within the series found in Table 1- 1. Total yield for each series conducted in the Marshall Islands is presented in the Table 3- 1.

Table 3-l Total Detonated Yield of Each Series Conducted in the Pacific Proving Ground.

Series	Start Date	End Date	Total Yield, kton
Crossroads	7/1/46	7/25/46	42
Sandstone	4/15/48	5/15/48	104
Greenhouse	4/8/51	5/25/51	399
Ivy	11/1/52	11/16/52	10,900
Castle	3/1/54	5/14/54	48,200
Redning	5/5/56	7/22/56	20,850
Hardtack I	5/6/58	8/19/58	28,026
Total			108,521

The next parameter in the equation is the fission fraction (F_f) of the device or series. Since the fission fraction of individual tests remains classified. calculations will have to rely on approximate information applied to test series. Table 3-2 lists the approximate fission and total yield of nuclear weapons tests conducted by all nations through 1958 (UNSCEAR 1988). The fission fraction (or percent fission) is the quotient of the fission yield and total yield. Since Ivy Mike (1 1/1/52) was the first true test of a thermonuclear device. all tests before this are considered 100% fission devices.

Table 3-2 Fission Percentages of Devices Listed by Year of Detonation.

start Date	End Date	Fission Yield, Mton	Total Yield, Mton	Percent Fission
1945	1951	0.8	0.8	100%
1952	1954	37	60	62%
1955	1956	14	31	45%
1957	1958	40	81	49%

Source: UNSCEAR 1988

The estimates of F_f are only approximations. In order to account for uncertainty in the approximations of F_f, uncertainty distributions need to be assigned. The distributions of F_f are assumed to be triangular. This study also assumes that with time the tests became more efficient which resulted in a lower percentage of yield coming from fission. Therefore, the most likely value for the 1952-1954 time period is 0.62, with a range from 0.40 to 0.80. For the 1955-1956 time period, the most likely value is 0.45, with a range from 0.30 to 0.62. For the 1957-1958 time period, the most likely value is 0.49, with a range from 0.20 to 0.60.

The final parameter needed in this equation is the radionuclide yield (Y_r). Table 3-3 lists the approximate yields of several fission and activation products per megaton of fission (Whicker and Schultz 1982).

Table 3-3 Approximate Yield of Selected Radionuclides per Megaton of Fission.

Radionuclide	Half-life	MCi
Fission products		
^{131}I	8.02 day	125
^{137}Cs	30.17 year	0.16
Activation products (soil)		
^{45}Ca	152 day	4.7E7

Source: Whicker and Schultz 1982

It is important to note here that estimates of the amount of ^{131}I produced and released from the testing in Nevada were calculated by the relationship of 150 thousand Curies of ^{131}I produced per kiloton (150 kCi kton^{-1}) of fission yield (NCI 1997). This estimate is 20 % higher (150 vs. 125) than the value shown in Table 3-3.

Further refinement of these methods is necessary in order to account for uncertainty in Y,. The approach to these refinements is discussed in the following paragraphs.

Uncertainty in Y_r can be estimated by simple energy and fission conversions. The first part of this conversion involves the amount of energy released per ton of TNT explosive energy equivalent. This conversion is 4.18E9 J ton^{-1} (TNT). Tons are converted to Megatons (Mton) by multiplying by 1E6 ton Mton^{-1}. Joules is converted to Million Electron Volts (MeV) by dividing by 1.6E-13 J MeV^{-1}.

Next, an estimate of the number of fissions produced per MeV is needed. These parameter estimates come from England and Rider (1994) where the number of fissions per MeV is 199.59 ± 0.75 MeV fission^{-1} for fast fission of ^{239}Pu. Finally, the model will need an estimate of the percent of fissions that result in ^{137}Cs production. This value from the same report is 6.58% ± 1% for fast fission of ^{239}Pu.

The calculations mentioned in the previous paragraph result in the number of ^{137}Cs atoms produced. This number is converted to activity (Bq) with the simple equation given below:

$$A = \lambda \cdot N$$

where

A = activity, Bq;

λ = decay constant for ^{137}Cs, 7.28E-10 s^{-1}; and

N = number of ^{137}Cs atoms.

The resultant parameter value for Y_r becomes 6.28E9 ± 9.47E8 Bq $Mton^{-1}$ (0.17 ± 0.03 MCi $Mton^{-1}$). This number compares well with the approximate number (0.16 MCi $Mton^{-1}$) in Table 3 -3.

Estimating Deposition from Global Sources

A general description of the methodology for estimating deposition from global sources is discussed in this section. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has developed and used these techniques for assessing global population doses from atmospheric weapons testing fallout.

Since most atmospheric weapons testing occurred in the Northern Hemisphere, a larger majority or' fallout occurred in that half of the globe. In addition, the distribution of fallout radioactivity changes with latitude, with most occurring in the 40-50 degree band and least occurring in the O-10 degree band closest to the equator (UNSCEAR 1993). Figure 3-l shows this latitude distribution of ^{90}Sr fallout deposition.

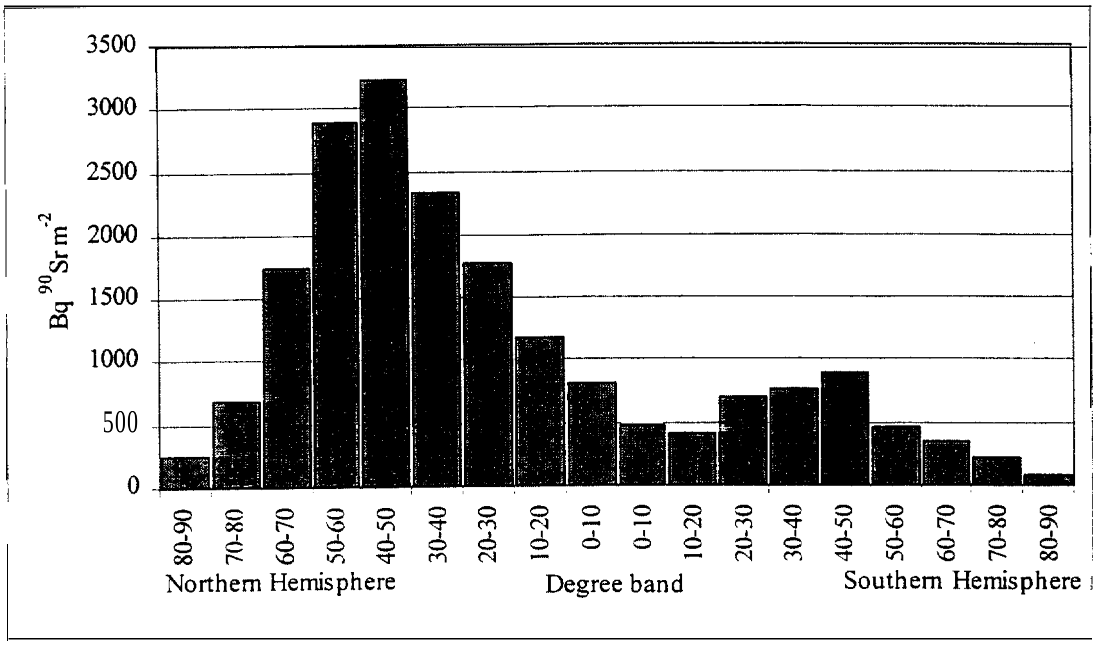

Figure 3-l Fallout Deposition Density per Latitude Degree Band.

The UNSCEAR method uses integrated fallout deposition measured from the global sampling network. From this data source, integrated deposition values are tabulated for each 1 O-degree latitude band along the globe. Since the Marshall Islands lie within latitudes of 4 to 14 degrees north of the equator, 0- 10 and 1 O-20 degrees latitude bands were selected from the tables. Integrated ^{90}Sr deposition in each band is reported in PBq (1 PBq = 10^{15} Bq). Values of integrated ^{90}Sr deposition in the O-l 0 degree band and the 10-20 degree band are 35.7 and 50.9 PBq respectively.

This method also uses the estimated land area present in each latitude band. Land area estimates for the O-l 0 degree band and the 1 O-20 degree band are 44.1E12 m^2 and 42.8E12 m^2 respectively.

The integrated deposition density becomes the quotient of the integrated deposition and the land area as shown in the following equation:

$$DEP_{ground} = \frac{A}{LA}$$

where

DEP_{ground} = deposition concentration of ^{90}Sr, PBq m^{-2};

A = activity of ^{90}Sr, PBq; and

LA = land area of latitude band: m^2.

Values of integrated ^{90}Sr deposition density using this technique are shown in Table 3-4.

Table 3-4 Latitudinal Distribution of ^{90}Sr Deposition from Atmospheric Testing.

Latitudinal band Degrees	Area of band $10^{12} m^2$	Integrated ^{90}Sr deposition PBq	Integrated deposition density Bq m^{-2}
1 O-20	42.8	50.9	1190
O-10	44.1	35.7	810

Other radionuclides are estimated from the respective fission product yield. Cesium-1 37 is estimated by multiplying the ^{90}Sr estimates by a ratio of ^{137}Cs to ^{90}Sr. This estimate is described by the Health and Safety Laboratory (HASL) as 1.6 ± 0.2. (Hardy 1981)

Further refinement of these methods is necessary in order to account for annual deposition estimates, the decay of these annual deposition estimates to 1982 (justification for this year is given in Chapter 5), and to subtract the PPG testing contribution to the annual deposition estimates. The approach to these refinements is discussed in the following paragraphs.

To account for annual deposition occurring in the RMI a surrogate data set containing annual ^{137}Cs deposition rates are needed. The chosen data set comes from the Riso National Laboratory, Roskilde, Denmark (RISO 1992). This data set contains annual ^{137}Cs deposition rates for three locations in Denmark from 1950 through 1991 (only data through 1982 was used). The locations include Denmark, Jutland, and the Islands as shown in Table 3-5.

Information from this table is presented in Figure 3-2. From this figure it can be seen that the heaviest deposition measurements were obtained for the mid-sixties. Also from this figure, it is evident that the test moratorium on October 3 1, 1958 had a significant impact on reducing the amount deposited for two years until testing resumed in September 196 1.

For each location, the annual ^{137}Cs deposition is divided by the cumulative ^{137}Cs deposition in 1982. The resultant value represents the fraction of deposition occurring in that year. The average and standard deviation of the three locations annual deposition fraction are calculated. These annual deposition fractions can then be multiplied by cumulative ^{137}Cs deposition estimates for the RMI latitude band to produce annual ^{137}Cs deposition estimates for the RMI.

The annual deposition estimates must be corrected for radioactive decay. This correction adjusts the annual deposition values to the cumulative deposition amounts remaining in 1982. For example, less than one half the amount deposited in 1950 remains in 1982. The radioactive decay equations are presented in the Correcting for Decay Section.

Table 3-5 Fallout Deposition Rates (Bq $^{137}Cs\ m^{-2}\ y^{-1}$) in Denmark 1950-1982.

Year	Denmark	Jutland	Islands
1950	1.243	1.302	1.184
1951	5.979	6.749	5.210
1952	11.722	13.261	10.182
1953	29.600	33.507	25.693
1954	112.539	127.398	97.680
1955	148.059	167.595	128.523
1956	183.579	207.792	159.366
1957	183.579	207.792	159.366
1958	254.678	288.245	221.053
1959	361.238	408.954	313.582
1960	67.488	76.427	58.608
1961	87.675	99.219	76.072
1962	439.738	472.179	407.296
1963	988.344	1092.418	884.270
1964	616.390	691.752	541.029
1965	234.077	248.877	219.277
1966	126.984	128.227	125.741
1967	61.982	69.619	54.346
1968	83.058	92.826	73.230
1969	61.272	73.467	49.077
1970	97.502	117.986	77.019
1971	89.155	102.179	76.131
1972	25.752	27.054	24.450
1973	11.366	12.728	9.946
1974	42.032	46.117	38.066
1975	24.509	26.758	22.259
1976	6.098	6.867	5.328
1977	22.733	23.976	21.430
1978	27.410	31.850	22.970
1979	9.827	10.301	9.235
1980	5.606	6.766	4.591
1981	17.059	18.316	15.948
1982	2.706	2.851	2.561
Total	444 1	4941	3941

Source: RISO 1992

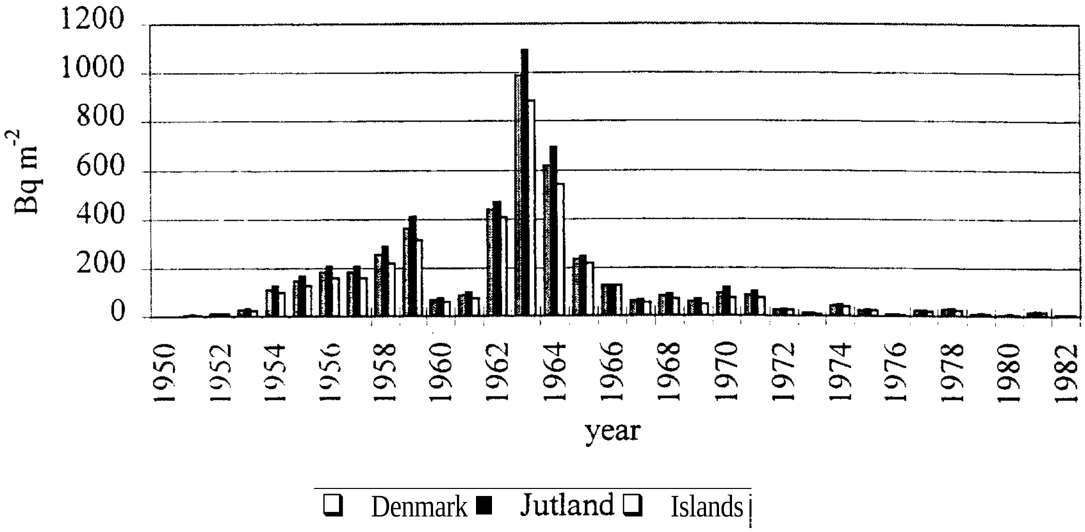

Figure 3-2 Annual ^{137}Cs Deposition in Denmark 1950-l 982.

To account for only the non-PPG testing contributions to the annual deposition estimates, the first estimate calculated is the amount due to testing at the PPG relative to the amount produced globally. UNSCEAR (1993) estimates a total yield of approximately 17-l megatons from ail weapons tested through 1958. The total test yield at the PPG through 1958 was approximately 108 megatons. It is, therefore, necessary to subtract 62% (=108/1 74) from the annual deposition estimates from 1950 through 1958. The following equation. derived for this study, is used to adjust the deposition estimates from 1950 through 1958:

$$DEP_{ground} = DEP_i \cdot (1 - 0.62)$$

where

DEP_{ground} = deposition of non-PPG sources, Bq m^{-2}; and

DEP_i = annual deposition in year i (1950 – 1958), Bq m^{-2}.

Estimating Deposition with Exposure Rate Data

A general description of the methodology for estimating deposition with exposure rate data is discussed in this section. Measurements of exposure rates at various times after the fallout arrives are decay corrected to a common time. This common (or normalized) time is set at 12 hours post detonation (H+12). This decay correction is accomplished with the use of Decay Factors (DF) obtained in the Hicks' Tables (Hicks 1984) and the following equation:

$$\dot{X}_{(H+12)} = \frac{\dot{X}_t}{DF}$$

where

$X_{(H+12)}$	= exposure rate at 12 hours post detonation, mR hr^{-1};
X_t	= exposure rate at time t post detonation, mR hr^{-1}; and
DF	= decay factor at time, t.

Decay Factors

Decay Factor (DF) tables are found in the publication by Hicks (1984). Hicks derived the DF values for six of the tests conducted at the Marshall Islands. The six tests include Mike, Bravo, Romeo, Yankee, Tewa, and Zuni. Three separate tables of DF values are provided for each test. The three tables represent three different levels of fractionation (1 .O, 0.5, and 0.1). Fractionation is defined as the ratio of non-volatile (refractory) to volatile elements present in the cloud. Therefore, a fractionation level of 0.5 indicates that one-half of the refractory (non-volatile) elements are present in the cloud. Each table is comprised of 3 1 values of Decay Factors from time zero to 50 years after detonation. Table 3-6 shows the DF values for each test at a fractionation level of

0.5 (justification for this fractionation level is given in Chapter 5) and from zero to 1,200 hours post-shot.

It is important to note that the table values for Romeo and Yankee are identical. This fact is made even more interesting by the recent release of declassified information from the DOE archives (USAF 1954). This information shows that although the total yields for Romeo and Yankee are different. their fission yields are identical.

Another use of these decay factor formulations is the calculation of exposure rate from previous tests. This calculation is especially important for tests within series conducted a few days apart. Exposure rate measurements taken after succeeding tests would likely include residual exposure rates from material previously deposited. These residual contributions to exposure rate must be subtracted from these measurements.

Table 3-6 Decay Factors for the Six Tests at a Fractionation Level of 0.5.

Hours	Mike	Bravo	Romeo	Yankee	Tewa	Zuni
0.00E+00	1.01E+02	1.04E+02	9.99E+01	9.99E+01	1.09E+02	1.07E+02
1.00E+00	2.97E+01	3.07E+01	2.96E+01	2.96E+01	3.25E+01	3.23E+01
2.00E+00	1.16E+01	1.20E+01	1.16E+01	1.16E+01	1.27E+01	1.27E+01
3.00E+00	6.23E+00	6.41E+00	6.22E+00	6.22E+00	6.75E+00	6.75E+00
4.00E+00	3.93E+00	4.03E+00	3.93E+00	3.93E+00	4.22E+00	4.22E+00
6.00E+00	2.14E+00	2.18E+00	2.15E+00	2.15E+00	2.24E+00	2.24E+00
9.00E+00	1.33E+00	1.34E+00	1.33E+00	1.33E+00	1.35E+00	1.35E+00
1.20E+01	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
1.50E+01	8.05E-01	8.00E-01	8.03E-01	8.03E-01	7.93E-01	7.94E-01
1.80E+01	6.70E-01	6.63E-01	6.67E-01	6.67E-01	6.53E-01	6.55E-01
2.10E+01	5.70E-01	5.63E-01	5.67E-01	5.67E-01	5.51E-01	5.53E-01
2.40E+01	4.88E-01	4.81E-01	4.85E-01	4.85E-01	4.68E-01	4.67E-01
4.80E+01	2.25E-01	2.22E-01	2.23E-01	2.23E-01	2.14E-01	2.12E-01
1.20E+02	8.29E-02	8.32E-02	8.20E-02	8.20E-02	8.29E-02	8.15E-02
2.40E+02	3.59E-02	3.64E-02	3.55E-02	3.55E-02	3.81E-02	3.79E-02
4.80E+02	1.35E-02	1.38E-02	1.32E-02	1.32E-02	1.49E-02	1.51E-02
7.20E+02	7.62E-03	7.73E-03	7.43E-03	7.43E-03	8.36E-03	8.52E-03
1.20E+03	3.45E-03	3.48E-03	3.35E-03	3.35E-03	3.74E-03	3.84E-03

Source: Hicks 1984

This correction will use the estimated $X_{(H+12)}$ exposure rate to calculate the residual exposure rates for subsequent tests in the series by the following formula:

$$\dot{X}_t = \dot{X}_{(H+12)} \cdot DF$$

where

X_t	= exposure rate at time t from previous detonation, mR hr^{-1};
$X_{(H+12)}$	= exposure rate at 12 hours post previous detonation, mR hr^{-1}; and
DF	= decay factor at time, t.

In order to account for times other than those listed in the tables and to make the most efficient use of spreadsheet formulations, a regression analysis was performed on the data in Table 3-6. The regression analysis was done with Microsoft Excel functions. It included time values from H+12 to H+1,200 hours. After the data were displayed in the chart, a regression trend line is superimposed on the source data. These regression trend lines could take several different forms: linear, logarithmic, exponential, power, and polynomial. A power function trend line best described (highest correlation coefficient, R^2) the data. The general form of this function is shown in the following equation.

$$DF = at^b$$

where

DF	= decay factor;
a	= multiplicative parameter, a;
b	= esponential parameter, b; and
t	= time of measurement, hours.

The equation parameters and their respective correlation coefficients (R^2) are very similar for the six tests. As stated previously, the parameters for Romeo and Yankee are identical. A table of the resultant parameters and R^2 coefficients are shown in Table 3-7.

Table 3-7 Equation Parameters for the Decay Factor Derivation.

	Equation Parameters		
Test	a	b	R^2
Mike	*22.72*	-1.2097	0.9968
Bravo	22.125	-1.2035	0.9967
Romeo	23.018	-1.2153	*0.9967*
Yankee	23.018	-1.2153	0.9967
Tewa	*24.888*	-1.2309	*0.9943*
Zuni	19.967	-1.1761	0.9973

Other researchers have reported decay characteristics of fallout. Haaland (1987) compared four decay approximations for Castle Bravo. The first was the standard decay approximation with a γ-decay exponent (n) of - 1.2 as represented by the following equation.

$$R(t) = t^n$$

The second was from the work of Lessard et al. (1985). This approximation uses y-decay exponents of -1.5 from 0.2 d to 0.3 d, -1.3 from 0.3 d to 2.2 d. and -1.4 from 2.2 d to 26 d.

The third was the Way-Wigner decay approximation. This approximation uses γ-decay exponents of -1.2 from 1 hr to 15 hr and the following equation for times greater than 15 hr.

$$R(t) = 0.092t^{-1.2} + 1.56t^{-1.4}$$

The fourth approximation is from the computations by Hicks with a 0.5 level of fractionation. The decay curves from these four approximations are shown in Figure 3-3. The four curves were normalized to 1 mR hr^{-1} at 12 hours. All these methods produce similar decay characteristics. However, Hicks estimates that his formulations of decay factors exhibit an uncertainty of approximately 20%. He attributes this uncertainty to the measurement error of typical Gieger Mueller (GM) survey instruments in use during atmospheric testing. This uncertainty range on his decay curve would therefore extend beyond the other decay curves.

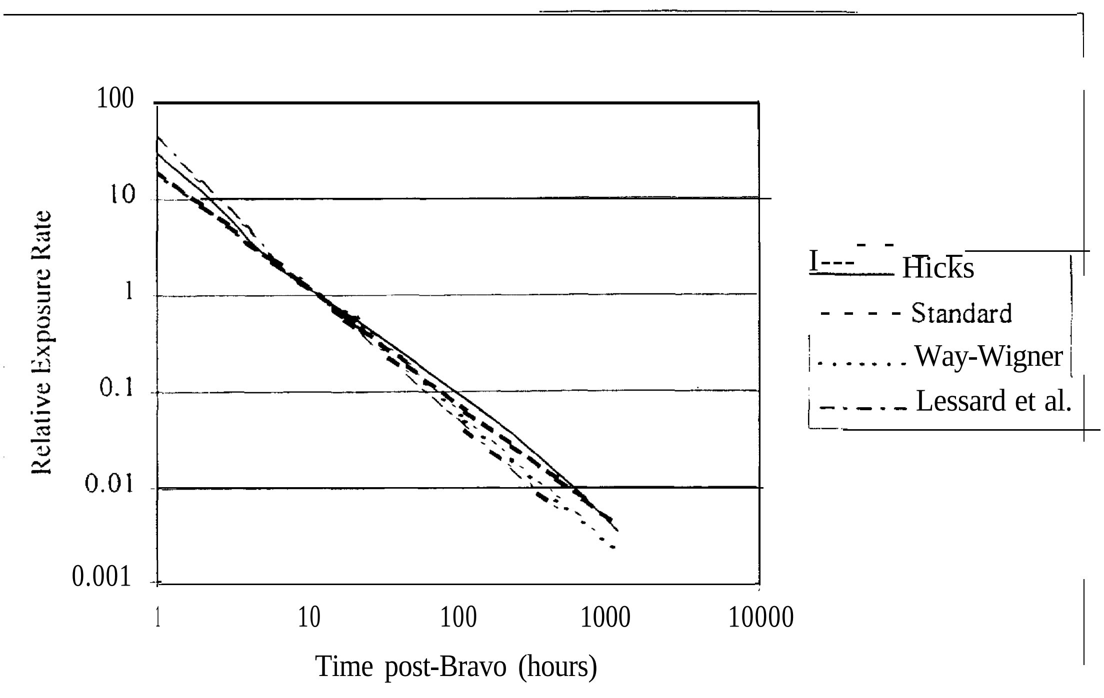

Figure 3-3 Comparison of γ-decay Approximations for Bravo

Normalized Deposition

Deposition estimates for ^{137}Cs are obtained by multiplying the normalized exposure rate by the Normalized Deposition (ND) factors for a particular time post detonation:

$$DEP_{ground} = \dot{X}_{(H+12)} \cdot ND_{^{137}Cs}$$

where

DEP_{ground} = ground level ^{137}Cs concentration, $\mu Ci\ m^{-2}$;

$X_{(H-12)}$ = exposure rate at 12 hours post detonation, $mR\ hr^{-1}$; and

ND_{137Cs} = normalized ^{137}Cs deposition, $\mu Ci\ m^{-2}$ per $mR\ hr^{-1}$ at H+12.

Normalized Deposition tables are also found in the publication by Hicks (1984). Hicks derived the ND values for approximately 177 radionuclides. Three separate tables of ND values are provided for each test. The three tables represent three different levels of fractionation (1 .0, 0.5, and 0.1). Each table is comprised of 3 1 values of ND values from time zero to 50 years after detonation. Table 3-8 shows the ND values for each test at a fractionation level of 0.5 and from zero to 1,200 hours post-shot. As before. the table values for Romeo and Yankee are identical.

The ND values for each test in Table 3-8 are identical from 1 to 1,200 hours post-test. As a result: there was no need to derive an equation with regression analysis in the Excel spreadsheets. The resultant ^{137}Cs deposition is the product of the exposure rate at 12 hours post-test ($X_{(H+12)}$) and the ND value from Table 3-8.

Table 3-8 Normalized Deposition Values for ^{137}Cs at the 0.5 Fractionation Level.

Hours	Bravo	Romeo	Mike	Zuni	Tewa
0.00E+00	7.29E-05	7.01E-05	7.06E-05	7.93E-05	7.79E-05
1.00E+00	7.86E-04	7.55E-04	7.61E-04	8.55E-04	8.40E-04
2.00E+00	7.86E-04	7.55E-04	7.61E-04	8.55E-04	8.40E-04
3.00E+00	7.86E-04	7.55E-04	7.61E-04	8.55E-04	8.40E-04
4.00E+00	7.86E-04	7.55E-04	7.61E-04	8.55E-04	8.40E-04
6.00E+00	7.86E-04	7.55E-04	7.61E-04	8.55E-04	8.40E-04
9.00E+00	7.86E-04	7.55E-04	7.61E-04	8.55E-04	8.40E-04
1.20E+01	7.86E-04	7.55E-04	7.61E-04	8.55E-04	8.40E-04
1.50E+01	7.86E-04	7.55E-04	7.61E-04	8.55E-04	8.40E-04
1.80E+01	7.86E-04	7.55E-04	7.61E-04	8.55E-04	8.40E-04
2.10E+01	7.86E-04	7.55E-04	7.61E-04	8.55E-04	8.40E-04
2.40E+01	7.86E-04	7.55E-04	7.61 E-04	8.55E-04	8.40E-04
4.80E+01	7.86E-04	7.55E-04	7.61E-04	8.55E-04	8.40E-04
1.20E+02	7.86E-04	7.55E-04	7.61E-04	8.55E-04	8.40E-04
2.40E+02	7.86E-04	7.55E-04	7.61E-04	8.55E-04	8.40E-04
4.80E+02	7.86E-04	7.55E-04	7.61 E-04	8.55E-04	8.40E-04
7.20E+02	7.86E-04	7.55E-04	7.61E-04	8.55E-04	8.40E-04
1.20E+03	7.86E-04	7.55E-04	7.61E-04	8.55E-04	8.40E-04

Source: Hicks 1984

Estimating Deposition with Gummed Film Data

Alternatively, gummed film data can be used to reconstruct deposition. Ground level concentrations of ^{137}Cs can be estimated using the normalized deposition factors for ^{137}Cs and the total deposition factors (also provided in Hicks' Tables) as shown in the following equation developed for this study:

$$DEP_{ground} = DEP_{gf} \cdot \frac{ND_{^{137}Cs}}{ND_{total}}$$

where

DEP$_{ground}$ = ground level ^{137}Cs deposition, μCi m^{-2};

DEP$_{gf}$ = measured gummed film deposition, μCi m^{-2};

ND$_{137Cs}$ = normalized ^{137}Cs deposition, μCi m^{-2} per mR hr^{-1} at H+12; and

ND_{total} = total deposition, $\mu Ci\ m^{-2}$ per $mR\ hr^{-1}$ at H+12.

Ratios of the ND values for ^{137}Cs and the total ND values are shown in the following Table (3-9). As before, the table values for Romeo and Yankee are identical.

Table 3-9 Normalized Deposition Values for ^{137}Cs to Total Normalized Deposition Ratios.

Hours	Bravo	Romeo	Mike	Zuni	Tewa
0.00E+00	5.44E-09	5.23E-09	5.19E-09	6.72E-09	6.18E-09
1.00E+00	3.00E-07	2.87E-07	2.86E-07	3.65E-07	3.39E-07
2.00E+00	8.47E-07	8.04E-07	8.06E-07	9.81E-07	9.20E-07
3.00E+00	1.44E-06	1.36E-06	1.36E-06	1.64E-06	1.54E-06
4.00E+00	1.95E-06	1.81E-06	1.81E-06	2.24E-06	2.09E-06
6.00E+00	2.76E-06	2.50E-06	2.50E-06	3.29E-06	3.01E-06
9.00E+00	3.78E-06	3.37E-06	3.34E-06	4.67E-06	4.22E-06
1.20E+01	4.73E-06	4.17E-06	4.14E-06	5.98E-06	5.35E-06
1.50E+01	5.70E-06	5.00E-06	4.94E-06	7.31E-06	6.51E-06
1.80E+01	6.66E-06	5.81E-06	5.77E-06	8.68E-06	7.71E-06
2.10E+01	7.71E-06	6.68E-06	6.62E-06	1.01E-05	8.95E-06
2.40E+01	8.76E-06	7.63E-06	7.53E-06	1.17E-05	1.03E-05
4.80E+01	1.79E-05	1.60E-05	1.58E-05	2.41E-05	2.14E-05
1.20E+02	5.04E-05	4.78E-05	4.79E-05	6.29E-05	5.83E-05
2.40E+02	1.33E-04	1.29E-04	1.30E-04	1.45E-04	1.39E-04
4.80E+02	3.85E-04	3.87E-04	3.90E-04	3.77E-04	3.72E-04
7.20E+02	6.66E-04	6.74E-04	6.73E-04	6.53E-04	6.46E-04
1.20E+03	1.25E-03	1.27E-03	1.26E-03	1.25E-03	1.26E-03

Source: Hicks 198-J

In order to account for times other than those listed in the tables and to make the most efficient use of spreadsheet formulations, a regression analysis was performed on the data in Table 3-9. The regression analysis was done with Microsoft Excel. The regression was performed on data from H+18 to H+480 hours. After the data were displayed in the chart, a regression trend line is superimposed on the source data. These regression trend lines could take several different forms: linear, logarithmic, exponential, power, and polynomial. A polynomial function trend line best described (highest correlation coefficient, R^2) the data. The general form of this derived polynomial function is shown in the following equation:

$$\frac{ND_{137Cs}}{ND_{total}} = at^2 + bt + c$$

where

ND_{137Cs}	= normalized ^{137}Cs deposition, μCi m^{-2} per mR hr^{-1} at H+12;
ND_{total}	= total deposition, μCi m^{-2} per mR hr^{-1} at H+12;
a	= multiplicative parameter, a;
b	= multiplicative parameter, b;
c	= additive parameter, c; and
t	= time of measurement, hours.

The equation parameters and their respective correlation coefficients (R^2=1 for all) are very similar for the six tests. As stated previously, the parameters for Romeo and Yankee are identical. A table of the resultant parameters and R^2 coefficients are shown in Tabie 3-10.

Tabie 3-l 0 Equation Parameters for the ND_{137Cs}:ND_{total} Derivation.

Test	Equation Parameters a	b	C	R^2
Mike	1E-9	3E-7	6E-7	1
Bravo	1E-9	3E-7	1E-6	1
Romeo	1E-9	3E-7	7E-7	1
Tewa	8E-10	4E-7	8E-7	1
Zuni	7E-10	4E-7	1E-6	1

The collection efficiency of the gummed film is related to the amount of rainfall. Rainfall amounts from light to heavy produce varying degrees of efficiency as reported by Beck (1990). Table 3-11 shows this collection efficiency as a function of reported rainfall. The uncertainty estimate is reported to be ± 25%.

Table 3-11 Efficiency of Gummed Film as a Function of Precipitation.

Precipitation number	Efficiency	Uncertainty	Range
0	0.20	0.15	0.25
1	0.20	0.15	0.25
2	0.30	0.23	0.38
3	0.30	0.23	0.38
4	0.25	0.19	0.31
5	0.15	0.11	0.19
6	0.10	0.08	0.13
7	0.07	0.05	0.09
8	0.05	0.04	0.06

Source: Beck 1990

Converting Area1 Deposition to Soil Concentration

Deposition values are normally reported as areal concentrations such as Bq m^{-2}. To compare these area1 concentrations (Bq m^{-2}) with reported soil measurements (Bq kg^{-1}) a conversion is needed. These soil concentrations are converted to areal concentrations with the following equation from Till and Meyer (1983):

$$DEP_{ground} = C_{soil} \cdot z \cdot \rho$$

where

DEP_{ground} = ground level ^{137}Cs deposition. Bq m^{-2};

C_{soil} = soil concentration of ^{137}Cs, Bq kg^{-1};

z = depth of soil sample. m; and

ρ = density of soil sample, kg m^{-3}.

This equation can aiso be modified to calculate soil concentrations from areal concentrations. The rearranged form of this equation is shown below.

$$C_{soil} = \frac{DEP_{ground}}{(z \cdot \rho)}$$

Correcting for Decay

These measurements and estimates must be decay corrected to the last year of fallout (1982). This decay correction is accomplished with the following equations. The first equation decay corrects pre-1982 values to the amount remaining in 1982.

$$A_{1982} = A_{pre-1982} \exp(-\lambda t)$$

This same equation can be modified to calculate 1982 values from post-l 982 values:

$$A_{1982} = \frac{A_{\text{post-1982}}}{\exp(-\lambda t)}$$

where

A_{1982}	= activity at 1982, Bq;
$A_{pre-1982}$	= activity pre-1982, Bq;
$A_{post-1982}$	= activity post- 1982, Bq;
λ	= decay factor for ^{137}Cs, ln(2)/30.17 y = 2.3E-2 y^{-1}; and
t	= time between measurement and 1982, y.

Spatial Analysis

Many researchers (Simon and Graham 1997) have described environmental concentrations in the RMI in relation to distance from the Bikini Atoll test site. Some (Takahashi et al. 1997) have even analyzed these concentrations with directional components (e.g. easterly or southerly directions). This research will address these distance and direction influences together. A method for accomplishing this is to calculate the arc-distance from Bikini Atoll. The arc-distance (also known as chord length along a circle) for a particular atoll is the product of the compass angle (in radians) and distance (measured in kilometers) from Bikini Atoll. The Bravo shot location on Bikini was chosen as the reference point.

Compass angle is calculated from digitized information on soil sample locations obtained from the NWRS spreadsheet files. These x and y coordinates are converted to compass angles using trigonometric methods. First the difference in the y and x coordinates for each sample location and the Castle Bravo test location are calculated. Then the angle (in radians) is obtained by calculating the angle whose tangent (arctangent) is Ay over Ax. This is accomplished with the use of the ATAN2 (x_num,y_num) Excel formula. This formula returns the arctangent of the specified x and y coordinates in radians as shown in the following equation:

$$\theta = ATAN2(x_1 - x_2, y_1 - y_2)$$

where

θ = angle, radians;

x_1 = x coordinate for sample location, km;

x_2 = x coordinate for Bravo shot location, km;

y_1 = y coordinate for sample location, km; and

y_2 = y coordinate for Bravo shot location, km.

The resultant angle is based on the mathematical coordinate system (where angle of 0 degrees points towards East on a compass heading). To convert this to compass angle (where true North is 0”) one-half π is added to the resultant angle.

Distance (or radius) is calculated using common trigonometric formulations. This formula is shown in the following equation:

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

where

d	= distance, km;
x_1	= x coordinate for sample location, km;
x_2	= x coordinate for Bravo shot location, km;
y_1	= y coordinate for sample location, km; and
y_2	= y coordinate for Bravo shot location, km.

The arc-distances are simply the product of the angle (in radians) and the distance (in kilometers) for each sample location. The final part of this spatial analysis was calculating the average arc-distance for those atolls having more than one soil sample location. This averaging of the multiple arc-distances across an atoll allows a more consistent treatment of data as soil concentrations are averaged across the atoll.

Uncertainty Analysis

This reconstruction involves the use of measurements, calculations and scientific judgments made on the basis of available dara. Methods of uncertainty analysis include (1) critical review, (2) determining subjective confidence bounds, and (3) propagation of error using analytical and Monte Carlo methods. Each includes statements of uncertainty and how this uncertainty is expressed in the results. (NAS, 1995)

Distributions of individual measurements include estimating survey meter error (e.g., ±20% for Geiger Muller instruments and ±10% for Ionization Chamber instruments) and counting errors for measurements of radioactivity in environmental media (e.g., collection efficiency of gummed film and counting errors associated with gross activity measurements for historical soil analyses versus reported errors from contemporary Gamma Spectroscopy systems). Rigorous methods will be applied to fitting parameters to appropriate distributions and estimating bias in these estimates.

Monte Carlo Methods

An uncertainty analysis can be performed using Crystal Ball Version 4.0. Crystal Ball is a Microsoft Excel Add-In developed by Decisioneering, Inc (1996). This Add-In uses Monte Carlo simulation techniques. Each parameter in a spreadsheet calculation is given a distribution of possible values instead of a single value. When Crystal Ball runs a Monte Carlo simulation, a random number is selected for each variable within this distribution. This process is repeated many times (5000 iterations for this work) computing a different outcome each simulation. The output from each simulation is computed and stored. When the simulation is complete, a distribution of outcomes is provided on a probability distribution graph. This process is depicted in Figure 3-4.

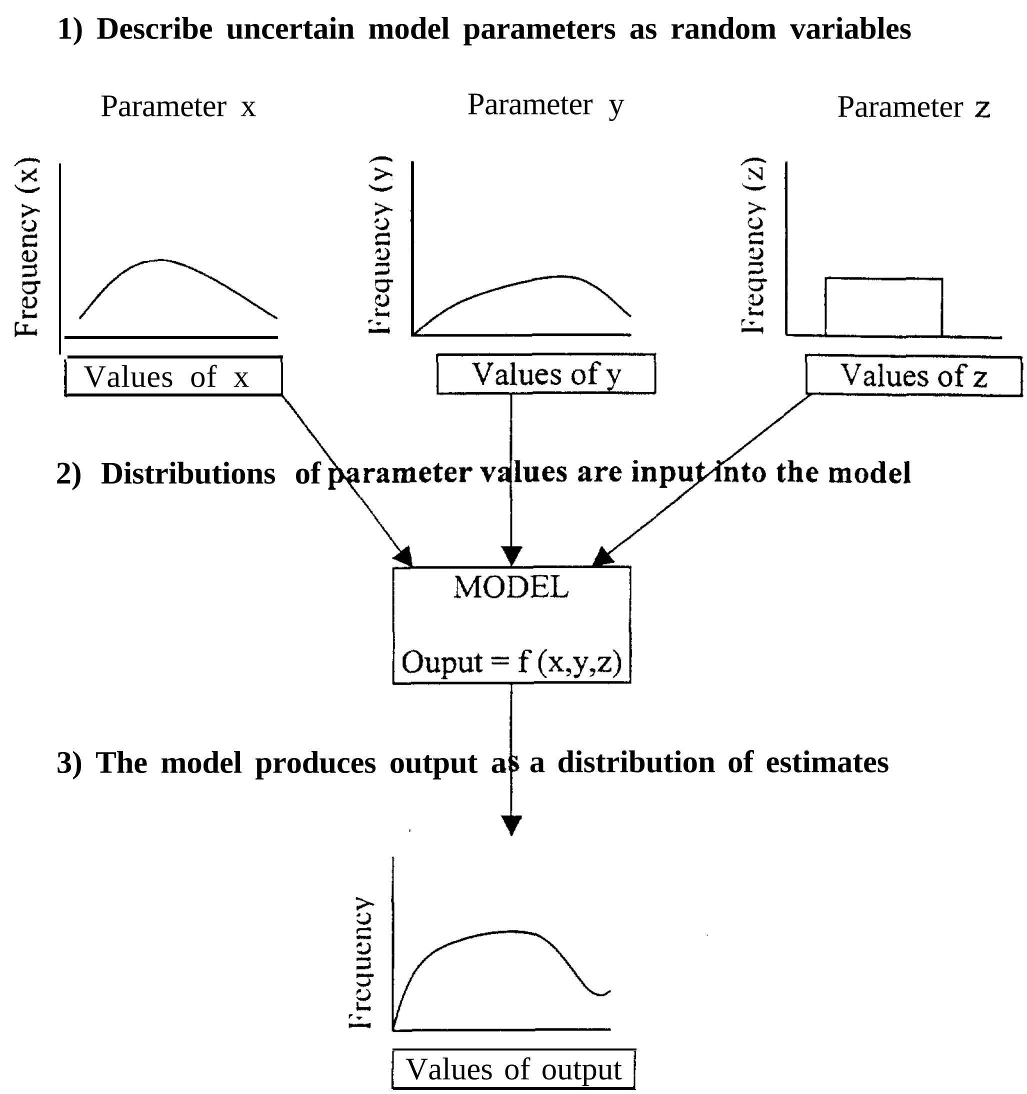

Figure 3-4 Steps in Uncertainty Analysis.

Quantifying Parameter Uncertainty

Each parameter used in the equations may be defined as a distribution of known or possible values. These distributions may be represented by normal, lognormal, uniform, or a variety of other frequency distributions. For example, when radiation survey instruments are calibrated, they are expected to measure known exposure rates to within a certain degree of accuracy. This accuracy is usually represented as a percentage error. Typical GM survey instruments in use during the atmospheric testing period report standard measurement errors of approximately ± 20%, while Ionization Chamber (Cutie Pie) survey instruments report measurement errors of ± 10 - 15% (Brady & Nelson 1985). These errors in measurement can be assumed to have a normal distribution.

Propagating Parameter Uncertaintv

Uncertainty is propagated through the spreadsheet equation with the Crystal Ball Add-In. Other calculations can be performed that obtain similar results as with Crystal Ball. These error propagation equations are specific to the mathematical operation being performed. For example. the equation below is used to propagate error from adding two or more values. The standard deviations of each parameter are used to produce a resultant standard deviation from the summation:

$$\sigma_{(x+y)} = \sqrt{\sigma_x^2 + \sigma_y^2}$$

where

$\sigma_{(x+y)}$ = combined standard deviation of parameter x and y;

σ_x = standard deviation of parameter x; and

σ_y = standard deviation of parameter y.

This equation is used in the calculation of the amount of ^{137}Cs in the 0- 15 cm soil profile. The standard deviations of each 5 cm layer are propagated in this manner producing the standard deviation of the total ^{137}Cs concentration in the O-l 5 cm layer.

Sensitivity Analvsis

A sensitivity analysis can also be performed with Crystal Ball (Decisioneering 1996). This analysis provides the level of influence each variable has on the outcome.

Crystal Ball calculates sensitivity by computing rank correlation coefficients between each assumption and forecast cell while running the simulation. The larger the value (both positive and negative) of the coefficient, the greater the impact of an assumption's uncertainty on the forecast results. Positive coefficients mean that the forecast increases with an increase in the assumption cell. Negative coefficients produce the opposite affect. This tool helps the user ascertain which variable in the model has the greatest or least influence on the outcome.

CHAPTER 4
DATA

Introduction

Input data and validation data sets are discussed in this chapter. Input data consist of historical monitoring data collected by various organizations. The historical monitoring data include exposure rate measurements from aerial and ground surveys, automatic monitor stations, and fallout deposition measurements from gummed film stations. Validation data sets come from contemporary measurements of ^{137}Cs in soil. All data obtained from referenced sources were entered into Microsoft Excel spreadsheets.

In many instances, date and time values for measurement data are reported as Greenwich Civil Time (GCT). This is a military convention used so that global measurements would be referenced to a common time. However, these GCT values need to be converted to local time in the RMI. The conversion to local time from GCT is an addition of 12 hours. This conversion was applied to all date/time measurements reported in GCT.

Input Data

Aerial Surveys

The U.S. Savy conducted Aerial Surveys in the Marshall Islands during Operation Castle using fixed wing aircraft (Breslin and Cassidy 1955). Three squadrons were assigned different flight patterns covering a large portion of the Pacific. One squadron, VP29, flew three flight patterns (designated ABLE, BAKER, and CHARLIE) over the Marshall Islands. The flight patterns for the Marshall Islands are included in Table 4-1.

Table 4-1 Aerial Surveys Conducted During Operation Castle.

ABLE	BAKER	CHARLIE
Kwajalein	Kwajalein	Kwaj alein
Lae	Namu	Kusair
Ujae	Ailinglaplap	Pingelap
Wotho	Namorik	Mokil
Bikini	Ebon	Ponape
Xilinginae	Kili	Ujelang
Rongelap	Jaluit	Kwaj alein
Rongerik	Mili	
Taongi	Amo	
Bikar	Maj uro	
Utirik	Aur	
Taka	Maloelap	
Ailuk	Erikub	
Jemo	Wotje	
Likiep	Kwaj alein	
Kwajalein		

These planes were equipped with sensitive, wide range, gamma scintillation instruments. The scintillation instruments were capable of measuring gamma intensities as low as 0.05 mR hr^{-1}. Measurements were generally made at an altitude of 61 m (200 feet). If the measured intensity was near the upper range of the instrument (100 mR hr^{-1}), another pass was made at a higher altitude. Corrections for differing altitudes were made so that all reported values were relative to the exposure rate at 1 m (-3 feet) above ground. Uncertainty in individual exposure rate measurements is estimated to be $\pm$ 25% with a normal distribution. This estimate is obtained from original datasheets provided by EML. These estimated uncertainties are a combination of instrument accuracy and uncertainty in altitude corrections.

Aerial Surveys were conducted one to three days after each test. This delay was intended to prevent measurement of passing cloud debris and maximize ground level measurements. Another reason for this delay was to minimize contamination of survey aircraft. Input data from these aerial surveys are provided in Figure 4-l. The full data set from which these values come is contained in Table A-l in the Appendix.

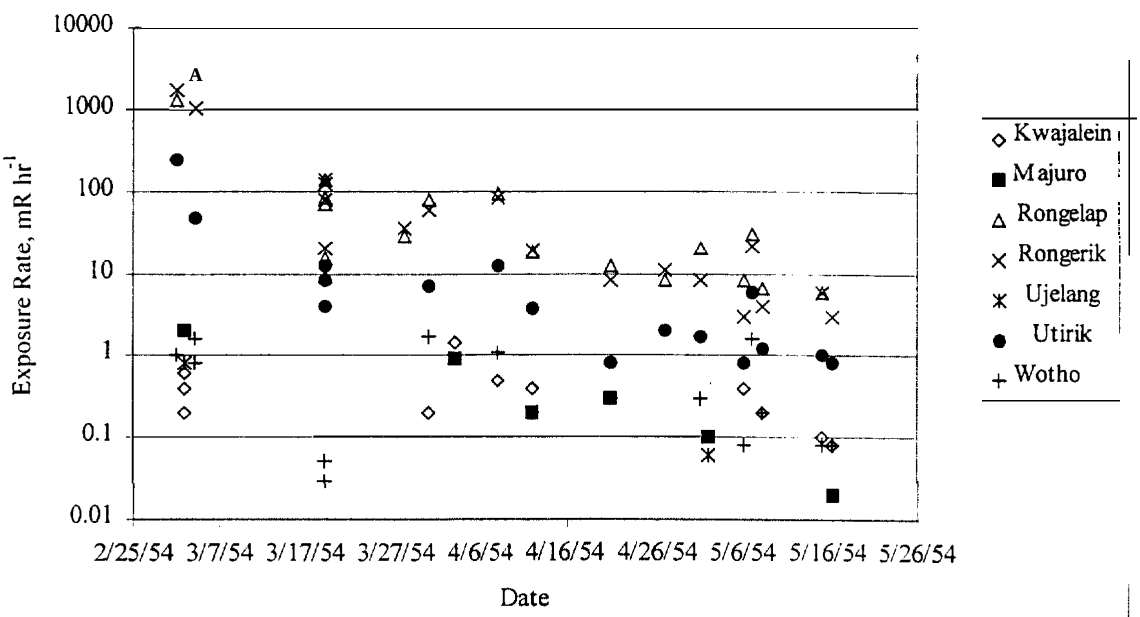

Figure 4-l Aerial Survey Measurements (mR hr^{-1}) During Operation Castle.

Fixed Monitors

During Operation Castle, the U.S. Weather Bureau (USWB), the U.S. Navy (USN), and the U.S. Air Force Air Weather Service (AWS) operated fixed automatic gamma monitoring stations at selected locations in the Pacific (Breslin and Cassidy

1955). The fixed monitor at Ujelang was unattended. The Atomic Energy Commission (predecessor of the Department of Energy) Health and Safety Laboratory (HASL) personnel retrieved data from this instrument periodically. Locations and responsible organizations are included in Table 4-2 below.

Table 4-2 Fixed Monitor Locations and Operating Agencies in the Marshall Islands Vicinity During Operation Castle.

Location	Operating Agency
Iwo Jima	AWS
Guam	AWS
Truk	USWB
Yap	USWB
Wake	USWB
Midway	USN
Rongerik	AWS
Majuro	AWS
Kusaie	AWS
Ponape	AWS
Kwaj alein	USN
Uj elang	HASL

Each fixed monitor station was equipped with one or two Gieger Mueller (GM) detectors. Several types of GM detectors were employed at different stations depending on availability of electricity. The first was a New York Operations (NYO) type TM-l-A, a 1 lo-volt AC unit with a detection range of 0.01 to 25 mR hr^{-1}. The next was a NYO type TM-4-A, a 1 lo-volt AC unit with a detection range of 0.1 to 100 mR hr^{-1}. The third unit was a NYO type TM-2-A, a battery operated DC unit with a detection range of 0.01 to 100 mR hr^{-1}. Uncertainty in individual exposure rate measurements is estimated to be ± 10% with a normal distribution. (Breslin and Cassidy 1955; Brady and Nelson 1985)

Periodic exposure rate measurements (mR hr^{-1}) were recorded and transmitted to the Joint Task Force (JTF) Headquarters. Exposure rate measurements were recorded at six, twelve, or twenty-four hour intervals depending on distance from the test site. The instruments operated at a range of 0.001 to 100 mR hr^{-1}. The fixed instrument at Rongerik operated only for a short time after Bravo. This instrument went off scale at 100 mR hr^{-1} jut after the Bravo fallout arrived. This instrument was subsequently removed from Rongerik. Data from the monitors at Kwajalein, Majuro, Rongerik and Ujelang are shown in Figure 4-2. The full data set is contained in Table A-2 in the Appendix.

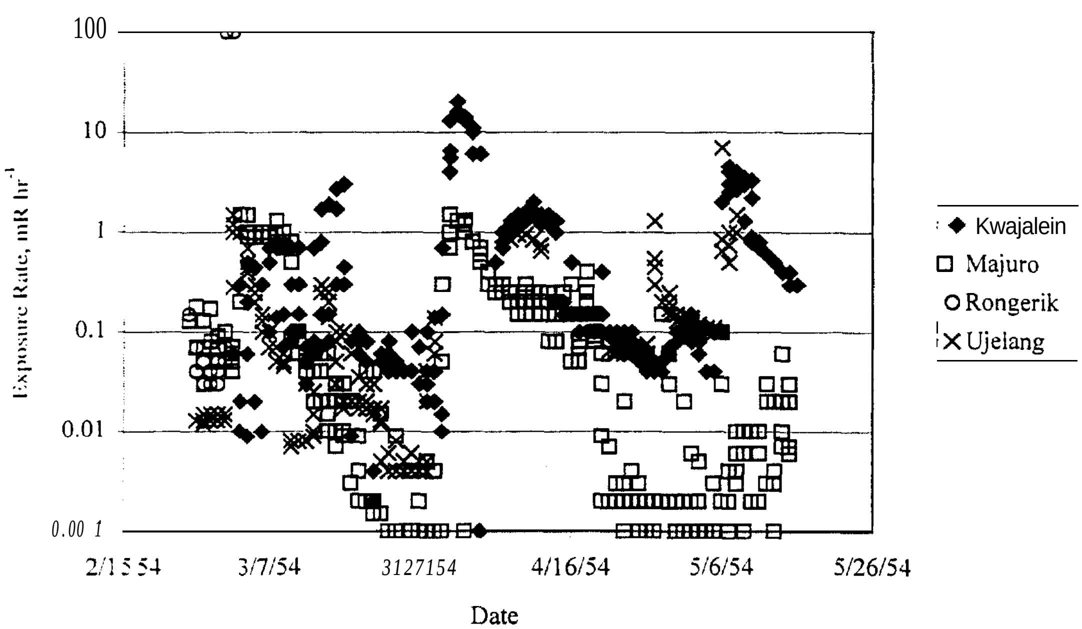

Figure 4-2 Fixed Monitor Measurements (mR hr^{-1}) During Operation Castle.

Ground Surveys

Severai groups within the Joint Task Force (JTF) performed ground level surveys during Operation Castle. These surveys are referenced in several JTF and Radiological Safety (RADSAFE) reports (JTF 1954a, JTF 1954b, JTF 1954c, and RADSAFE 1954).

Each ground surveyor was equipped with either an ionization chamber or Gieger Mueller (GM) survey meter. Several types of ionization chamber instruments were in use during Operation Castle. The two types most frequently used were an AN/PDR-39 and AN/PDR-T1B (the AN/PDR-T1B was also known as the AN/PDR-39). Each detector had five scales ranging from 0 to 50,000 mR hr^{-1}. Each instrument had a reported accuracy of 15% (Brady and Nelson 1985). Therefore, uncertainty in individual exposure rate measurements for these instruments is estimated to be ± 15% with a normal distribution.

Two types of GM survey meters were employed during Operation Castle. The first was a Beckman model MX-5 with three scales ranging from 0 to 20 mR hr^{-1}. This instrument had a reported accuracy of ± 10%. Therefore, uncertainty in individual exposure rate measurements from this instrument is estimated to be ± 10% with a normal distribution. The next instrument was an AN/PDR-27F with four scales ranging from 0 to 500 mR hr^{-1}. This instrument had a report accuracy of ± 20% (Brady and Nelson 1985). Therefore, uncertainty in individual exposure rate measurements for this instrument is estimated to be ± 20% with a normal distribution.

Ground level survey exposure rate measurements (mR hr^{-1}) were recorded and transmitted to the Joint Task Force (JTF) Headquarters. These surveys were conducted during the evacuation of several atolls post-Bravo (JTF 1954a) and during two soil and water sampling missions (JTF 1954b and JTF 1954c) conducted several days later at many offsite atolls. Exposure rate measurements were recorded at waist height or approximately one meter (3 feet) above ground.

The University of Washington's Applied Fisheries Laboratory (UWAFL) also performed ground level surveys as part of their sampling missions to various atolls. These sampling missions occurred during or just after major tests or test Operations. Exposure rate measurements were recorded on sampling data sheets and reported in sampling mission reports. Uncertainty in individual exposure rate measurement is estimated to be ± 10% with a normal distribution.

The Public Health Service (PHS) conducted ground level surveys (readings at 1 m or 3 ft above ground) during Operation Redwing. PHS personnel were stationed on Rongerik, Ujelang, Utirik, and Wotho. Four readings were taken daily at six-hour intervals. These four readings were averaged for a daily exposure rate value (PHS 1954). Input data of average daily exposure rates are shown in Figure 4-3. Uncertainty in individual exposure rate measurements is estimated to be ± 10% with a normal distribution. The complete data table is found in Table A-3 of the Appendix.

The PHS also conducted ground level surveys during Operation Hardtack I. PHS personnel were stationed on Rongelap, Ujelang, Utirik, and Wotho. Four readings were taken daily at six-hour intervals. These four readings were averaged for a daily exposure rate value (PHS 195 8). Input data from these average daily exposure rates are shown in Figure 4-4. Uncertainty in individual exposure rate measurements is estimated to be ± 10% with a normal distribution. The complete data set is contained in Table A-4 of the Appendix.

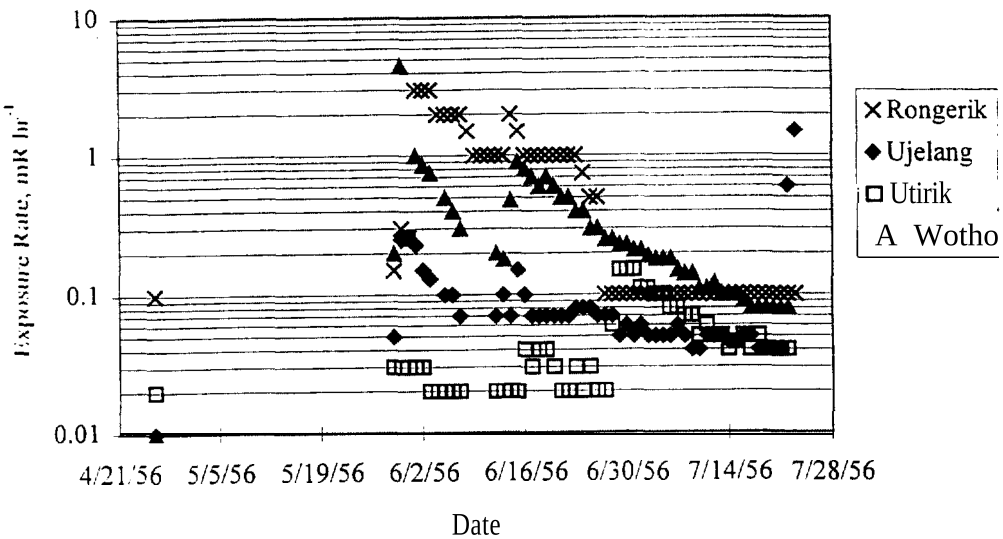

Figure 4-3 Average Daily Exposure Rate (mR hr^{-1}) Measurements during Operation Redwing.

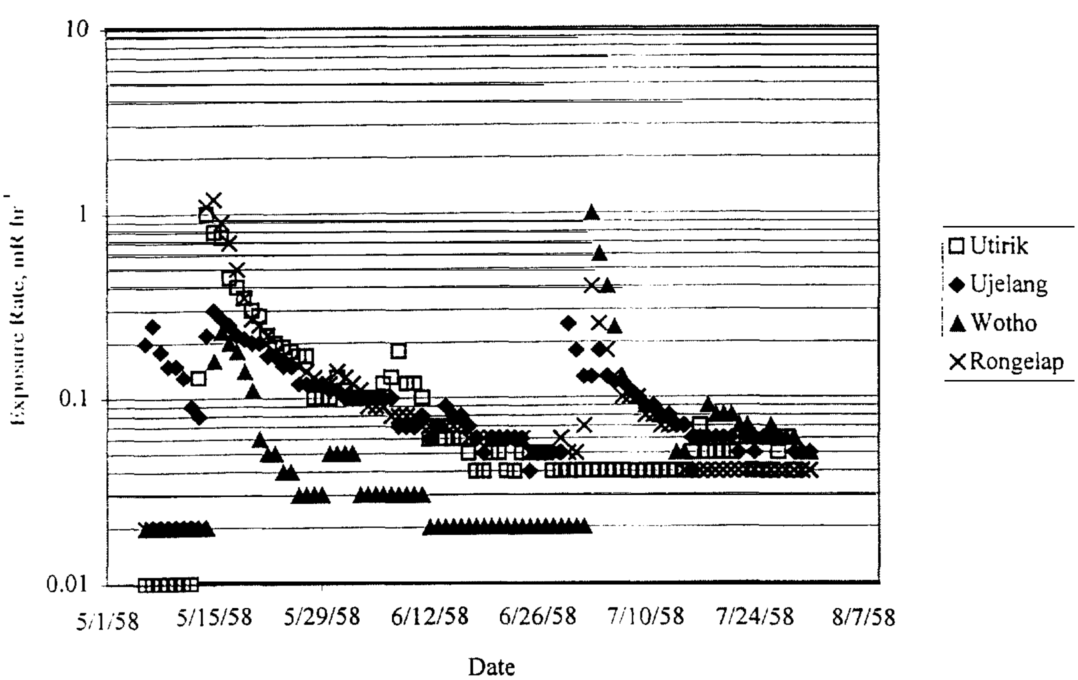

Figure 4-4 Average Daily Exposure Rate (mR hr^{-1}) Measurements during Operation Hardtack I.

<u>Gummed Film Measurements</u>

The Health and Safety Laboratory (HASL) conducted a world wide gummed film sampling program beginning in 1952 (Eisenbud 1953). Two gummed film collection stations were in place at Kwajalein and Majuro Atolls. The collectors consisted of a 30 cm x 30 cm (one foot by one foot) square “sticky paper” similar to household flypaper. Two collectors (for duplicate analysis) were placed in the open for 24-hour intervals. At the end of this period the paper was removed, folded, and shipped to the HASL in New York. Samples were ashed at about 500-550 ^{o}C and counted for gross beta activity in disintegrations per minute per square foot (dpm ft^{-2}) (Beck et al. 1990). Uncertainty in individual gummed film measurements is estimated to be ± 25% with a normal distribution.

The U.S. Naval Radiological Defense Laboratory (USNRDL 1953) reported gummed film measurements during Operation Ivy. Measurements were reported in counts per minute per square foot (cpm ft^{-2}). These count rates were converted to dpm ft^{-2} assuming a counting efficiency of 50%. This is the assumed counting efficiency of typical laboratory GM counters of the time.

Gummed film measurements for Operations Castle, Redwing and Hardtack I were obtained from the EML and US Weather Bureau (US Weather Bureau 1955). The gummed film locations at Kwajalein did provide a good record of distant fallout from the Ivy, Castle, Redwing, and Hardtack I Series in the Marshall Islands. However, some data gaps exist in the data set for Kwajalein. These gaps in the data include several days of missing gummed film measurement data for the Bravo, Romeo, and Yankee tests. These data gaps are reconstructed using exposure rate measurements made on Kwajalein. This data gap reconstruction is described in the next chapter.

The gummed film measurement data set for Majuro was thrown out by HASL during an evaluation of ^{90}Sr deposition for Project Sunshine (personal communication with Harold Beck of EML. 1997). The only other source for these data is the U. S. Weather Bureau (1955). This reference source only contains data from the Castle Series. Figure 4-5 displays the gummed film measurements on Kwajalein from 1954 through 1958. The complete data set is in Table A-5 in the Appendix.

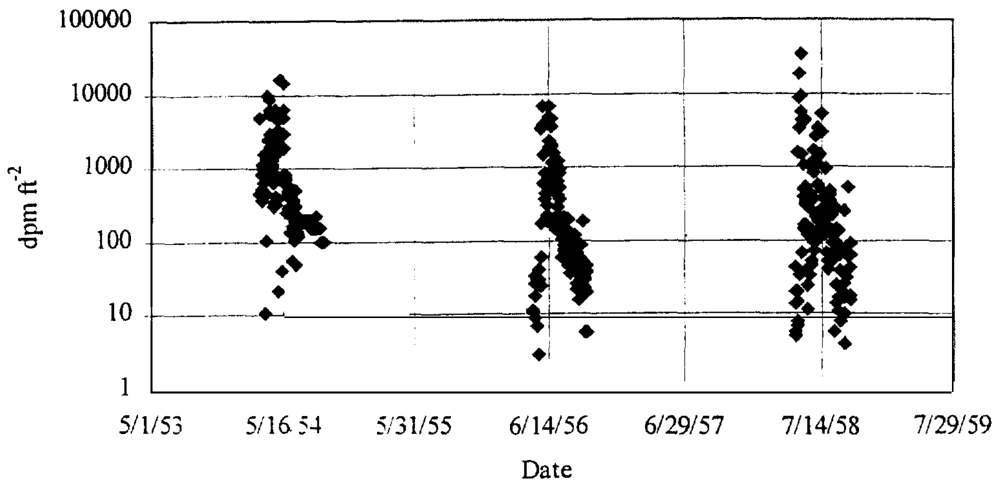

Figure 4-5 Gummed Film Measurements at Kwajalein, 1954 through 1958.

Soil Density

Soil density is an important parameter in the equation for converting area1 deposition densities to soil concentrations. Values from historical and contemporary literature are ranging but consistent. The University of Washington Radiation Biology

Laboratory analyzed soil from Enewetak, Bikini, and Rongelap in 1964 (Gessel and Walker 1992). Soil densities from this study ranged from 0.84 to 1.33 g cm”. The average value from this data set is 1.2 g cm^{-3}.

The Soil Conservation Service, US Department of Agriculture, measured soil densities in several mid-belt atolls (DOA 1989). These mid-belt atolls included; Airik, Arno, Majuro, Mili, and Taroa. Their soil density measurements were only listed as ranges. The values for bulk (dry) density in soil profiles range from 1.2 to 1.4 g cm^{-3} down to about 32 cm depth.

The Nationwide Radiological Survey (NWRS) also measured soil density as part of their radiological survey. Values obtained from the spreadsheet files range from 0.91 to 1.57 g cm^{-3}. The average value from this data set is 1.3 g cm”. Other tables in this spreadsheet lists soil densities from Bikini and Enewetak studies that range from 0.59 to 1.6 g cm^{-3}.

A statistical analysis was performed on the combined data from two studies of soil density. The results of the frequency distribution are shown in Figure 4-6. Based on these results, a triangular distribution was assumed for the uncertainty analysis with a most likely soil density of 1.2 g cm^{-3} and a range from 0.59 to 1.6 g cm”.

Validation Data

Contemporary Soil Samples

Soil samples collected from the RMI in recent years contain ^{137}Cs from both locally and globally produced sources. These samples hold a cumulative record of ^{137}Cs deposited. These soil data represent the observed environmental concentrations from which methods for estimating deposition can be validated.

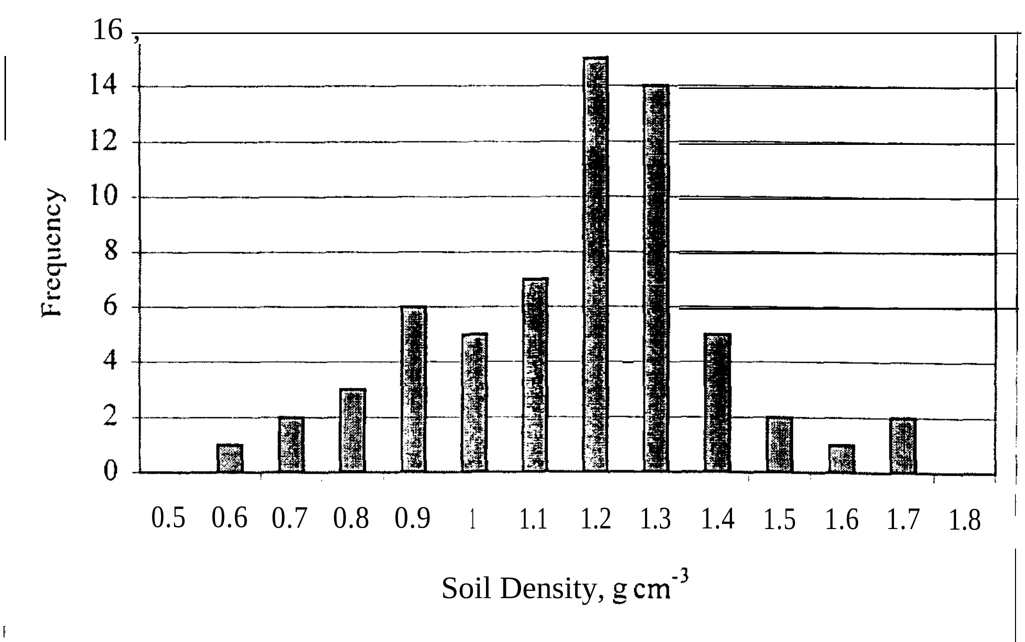

Figure 4-6 Frequency Distribution of Soil Densities in the Marshall Islands.

Nationwide Radiological Survey

Simon (1994) conducted the most extensive soil sampling across the entire Marshall Islands as part of the Nationwide Radiological Survey (NWRS). This survey included approximately 200 soil profiles and 1300 In-Situ gamma spectroscopy analyses. The data were collected from October 1990 to April 1994. Contemporary ^{137}Cs concentrations in soil across all atolls ranged from 0.4 to 10,5 15 Bq kg-‘.

Soil profile samples were collected at depth increments of 5 cm to a total depth of 30 cm. Samples were dried, crushed, and analyzed in NWRS laboratory in Majuro. The gamma spectroscopic analysis was performed using High Purity Germanium (HPGe) detectors. Minimum Detectable Activity (MDA) concentration for ^{137}Cs was reported as 0.3 Bq kg^{-1} for a 12-hour counting period (HPS 1997).

Data files from the NWRS were obtained through permission of the RMI government. Data from Kwajalein, Majuro, Rongelap, Rongerik, Ujelang, Utirik, and Wotho were re-analyzed for use in this assessment. This analysis is found in Chapter 5. Uncertainty in the atoll average soil concentration is based on the mean and standard deviation of the data set. The distribution of atoll-specific soil concentrations is assumed to be lognormai.

CHAPTER 5
CALCULATIONS AND ASSUMPTIONS

Introduction

This chapter introduces the calculations performed with the input of historical monitoring data. The assumptions used in the methods are explained. All data (with associated and derived uncertainties) used by the model are discussed. Finally, a Monte Carlo sensitivity analysis and a qualitative sensitivity analysis are used to assess the relative importance of different variables on the model's predictions.

Assumptions

Use of Hicks Tables for other than the Six Shots. Hicks provided decay factor and normalized deposition tables for only six test detonations in the Pacific. This research intends to reconstruct deposition from 17 tests (see test yield assumption below). Comparing the table values for the six tests reveal that differences between tests at various times post-detonation are quite small (standard deviation 5.7%). This is well within the range of uncertainty in exposure rate measurements with GM or ionization chambers in use at this time. Therefore, this research will assume that the Hicks tables are valid for the test for which they were derived and for subsequent tests until the next test for which Hicks derived table values. For example, Hicks tables for Zuni will also be used for Dakota, Apache, and Navajo. Table values for Tewa will also be used for Fir, Koa, Walnut, Oak, Poplar, and Pine.

Timing and Weathering of Exposure Rate Measurements. Fallout Time of Arrival (TOA) is an important factor in determining when to use exposure rate measurements. Exposure rate measurements taken shortly after the cloud arrives will include cloud shine and immersion components that could exaggerate the deposition estimates. The TOA estimates made at the time of Castle Bravo are shown in Table 5-l (Maynard 1954). As shown in this table the majority of atolls experienced fallout TOA within two days. Because of the effects of fallout TOA on measurements, this research will limit its use of exposure rate measurements to at least 48 hours (2 days) post test.

Table 5-1 Fallout Arrival Time for Castle Bravo.

Location	Fallout Arrival Time Hours
Ailinginae	3.6
Enewetak	5.4
Rongelap	5.6
Rongerik	8
Wotho	13.2
Bikar	16.3
Taka	20.3
Utirik	21.6
Jemo	24.8
Likiep	26.2
Ailuk	27.1
Mejit	30.2
Ujae	37
Wotje	39
Lae	39
Erikub	40
Maloelap	42.3

Source: Maynard 1954

Weathering is another important factor to consider in the use of measurement data. The effects of weathering are mainly due to rainfall. This effect was noticed about two weeks after Castle Bravo (Dunning 1957). A strong storm occurred which reduced the measured exposure rates on Rongelap Atoll. These measurements were well below those values expected from the standard decay curve. Because of the combined effects of fallout TOA and weathering on measurements, this research will limit its use of exposure rate measurements between 48 and 480 hours (2 to 20 days) post test.

Test Yield. Test yield is an important consideration for estimating deposition patterns in the Marshall Islands. Since low yield devices produce significantly less fallout at large distances, this research will reconstruct deposition patterns for device yields greater than one megaton. Based on this assumption, the following 17 tests in Table 5-2 are selected for reconstructing deposition of ^{137}Cs.

Table 5-2 Tests Greater than One Megaton.

Test	Local Date	Local Time
Mike	11/1/52	7:15 AM
Bravo	3/1/54	6:45 AM
Romeo	3/27/54	6:30 AM
Koon	4/7/54	6:20 AM
Union	4/26/54	6:10 AM
Yankee	515154	6:10 AM
Nectar	5/14/54	6:20 AM
zuni	5/28/56	5:56 AM
Dakota	6/26/56	6:06 AM
Apache	7/9/56	6:06 AM
Navajo	7/11/56	5:56 AM
Tewa	7/21/56	5:oo AM
Fir	5/12/58	5:50 AM
Koa	5/13/58	6:30 AM
Walnut	6/l 5/58	6:30 AM
Oak	6/29/58	7:30 AM
Poplar	7/13/58	3:30 PM
Pine	7/27/58	8:30 AM

Test Configuration. Another important consideration is the test configuration. Underwater tests produce significantly less fallout than surface tests conducted on towers or barges. In addition, there were no underwater tests greater than one megaton. Airdrop tests produce significantly less fallout dependent on the altitude of detonation and whether the fireball touches the ground. Cherokee was one such airdrop test detonated at a height of 1,524 m (5,000 ft) (DNA 1982c) that resulted in no detectable fallout on off-site atolls. Therefore, this research will not reconstruct deposition from underwater or airdrop test configurations.

Fractionation. Fractionation is defmed as the ratio of non-volatile (refractory) to volatile elements present in the cloud. Therefore, a fractionation level of 0.5 indicates that one-half of the refractory (non-volatile) elements are present in the cloud. As the cloud travels further from the test site, the level of fractionation decreases. The level of fractionation is important for determining which Hicks table to use. Researchers of the Utah thyroid disease study also evaluated this for their project (Utah 1992). They determined that a fractionation level of 0.5 best describes fallout patterns at large distances. Therefore, this research will use Hicks tables at the 0.5 level of fractionation.

Distribution of Global Fallout. The distribution of fallout from global sources has already been discussed in the Methods Chapter. It has been shown that fallout deposition is highest at the 40-50 degree latitude band and is lower closer to the equator. However, this effect can be altered due to local conditions such as rainfall. In the description of the Marshall Islands discussed in Chapter 1, it was noted that average annual rainfall is lowest in the northern atolls and greatest in the southern atolls. Simon (1996) concluded that this rainfall pattern would produce a uniform distribution of global fallout in the Marshall Islands. This research will therefore assume that globally produced ^{137}Cs deposition patterns in the Marshall Islands are uniformly distributed.

Cessation of Global Fallout. The final year of global fallout is important because it provides a reference point from which other measurements can be compared. A quote from the 1993 UNSCEAR report is as follows,

> "Because the last atmospheric nuclear weapons test occurred in 1980, and deposition of radioactive aerosols takes place within a few years, it *can* be considered that the deposition of ^{90}Sr produced by past atmospheric tests is essentially complete.. . . ^{90}Sr is used as a fallout indicator for all long-lived radionuclides."

Therefore, in this analysis the year 1982 was chosen as the reference year for comparing historical and/or contemporary measurements.

Selection of Atolls based on available data. Ideally one would like to have data available from all atolls and from all tests conducted in the Marshall Islands to reconstruct ^{137}Cs deposition for even- atoll. This, however, is not the situation. Based on the information collected, atolls with enough data to adequately estimate ^{137}Cs deposition include the following: Kwajalein, Majuro, Rongelap, Rongerik, Ujelang, Utirik, and Wotho.

Production Estimates

Calculations are presented on the estimated ^{137}Cs produced by testing in the Marshall Islands. The product of total yield of the Castle series alone (48.2 megatons), fission yield fraction (0.62), and the radionuclide yield (0.16E6 or 160,000 Ci) per megaton fission produce a deterministic result of 1.8E17 Bq (4.8E6 Ci).

$$P_{137Cs} = 48.2 \cdot 0.62 \cdot 0.16E6 = 4.8E6Ci$$

Using the data and the equation discussed in the methods section a median estimate of 3.4E17 Bq (9.2E6 Ci) of ^{137}Cs were produced by testing in the Marshall Islands. A list of these estimates is presented in Table 5-3.

Table j-3 Estimated Fission Yield and Production of ^{137}Cs by Test Series.

Series	Fission Yield (kt)	^{137}Cs production estimate, Bq		
		50th (median)	5th	95th
Crossroads	42	2.35E+14	2.14E+14	2.54E+14
Sandstone	104	5.81E+14	5.30E+14	6.28E+14
Greenhouse	399	2.22E+15	2.03E+15	2.41E+15
Ivy	6722	3.75E+16	3.43E+16	4.06E+16
Castle	29723	1.66E+17	1.52E+17	1.80E+17
Redwing	9416	5.26E+16	4.80E+16	5.69E+16
Hardtack I	13840	7.73E+16	7.06E+16	8.36E+16
Total	60246	3.36E+17	3.07E+17	3.64E+17

Estimates of the amount of ^{131}I produced and released from the testing in Nevada (NCI 1997) were calculated by the relationship of 5.55E18 Bq (150 thousand Curies) of ^{131}I produced per kiloton of fission yield (150 kCi kton^{-1}). An estimated 150 million curies of ^{131}I were produced at the NTS. Using this conversion with the estimated total fission yield at the PPG (60,246 kilotons) results in an estimated 3.3E20 Bq (9E9 Ci) of ^{131}I

Global Fallout Estimate

Results of calculations are presented on the estimated ^{137}Cs deposited in the Marshall Islands from global sources. From these calculations the estimated median ^{137}Cs &position in 1982 for the Marshall Islands was 691 Bq m^{-2} with 5th and 95th percentiles of 492 and 925 Bq m^{-2} respectively. The minimum and maximum values for the uncertainty range were 417 and 1076 Bq m^{-2} respectively, with an arithmetic average of 69‾ Bq m^{-2}.

Also from these calculations the years of greatest deposition can be estimated. Figure 5-1 gives the annual global deposition estimates for the Marshall Islands. As is seen in this graph, the heaviest depositions occurred during the years 1962 to 1964. This occurred due to the increased atmospheric testing at the end of the moratorium of 196 1. Another important result of this calculation is that the impact on measurements during testing from global sources was minimal. This is especially true for the years 1952 through 1958.

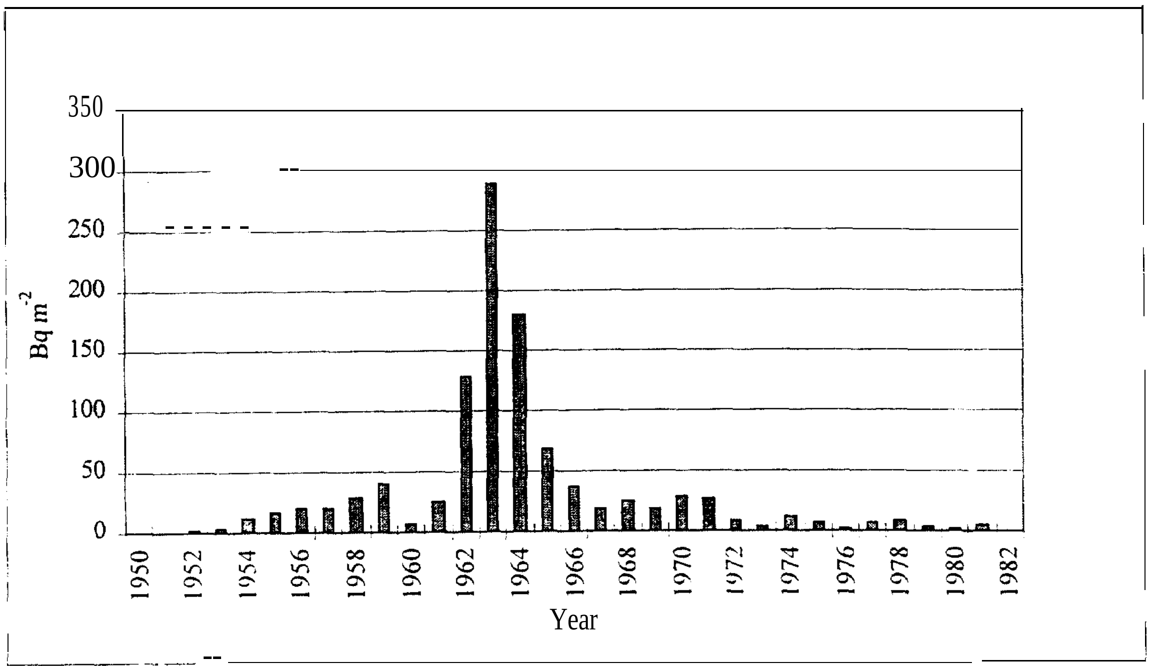

Figure 5-1 Annual Cesium Deposition Estimates from Global Sources in the Marshall Islands.

Deposition Estimates

This section discusses the calculations performed using exposure rate data and gummed film data. Deposition patterns for Kwajalein and Majuro are calculated using gummed film data. As already discussed, Majuro is only a partial data set. Deposition patterns for the remaining atolls are calculated using exposure rate data. All calculations were performed using spreadsheets in Microsoft Excel.

Calculations Based on Exposure Rate Data

This section discusses the calculations performed using exposure rate data. The atolls for which deposition is estimated from exposure rate information include; Rongelap, Rongerik. Ujelang. Utirik, and Wotho. Deterministic calculations for each atoll are presented by test series. Deposition estimates for each test within the series are summed to produce a series total. Results of stochastic calculations (with uncertainty analysis) are presented at the end of each atoll-specific section.

Rongelap

Ivy Series, The aerial survey over Rongelap on 1 1/3/52 detected no exposure rate data for Ivy Mike. Therefore, no ^{137}Cs deposition on Rongelap is estimated from the Ivy Mike test.

Castle Series. The following table (5-4) presents the calculations of $X_{(H+12)}$ from Castle Bravo. The final measurement in this table (1.5 mR hr^{-1} from an aerial survey on 3/19/54) was not used in the calculation of the average $X_{(H+12)}$ due to the storm that reduced exposure rate readings. However, this value was used in the calculation of residual exposure rate from Castle Bravo while measuring exposure rates for subsequent Castle tests.

Table j-4 $X_{(H+12)}$ Exposure Rate Calculations Post-Bravo at Rongelap.

Type of Measurement	Local Date	Local Time	mR hr^{-1}	Hours post	$X_{(H+12)}$
Aerial Suney	3/4/54	2:10 PM	2700	79.42	23606.1
Ground Survey	3/3/54	10:45 AM	1473	52.00	7736.2
Ground Survey	3/8/54	2:00 PM	375	175.25	8499.4
Ground Survey	3/11/54	10:00 AM	210	243.25	7062.4
Ground Survey	3/11/54	11:00 AM	170	244.25	5745.5
Ground Survey	3/11/54	11:00 AM	145	244.25	4900.5
Aerial Survey	3/19/54	5:22 PM	15	442.62	1036.8
				Average	8369.6

For the remaining tests in the Castle series the measurements of exposure rate for residual exposures are corrected from previous tests like Bravo. These corrections of exposure rate are presented in Table 5-5.

Table 5-5 Corrected Exposure Rate Measurements at Rongelap from Castle Residuals.

Test	Type of Measurement [a]	Local Date	Local Time	Value $mR\ hr^{-1}$	Residual Exposure $mR\ hr^{-1}$ Bravo	Romeo	Koon	Union	Net
Romeo	AS	3/31/54	10:22 AM	78	8.3				69.7
Koon	AS	4/12/54	11:09 AM	17.8	5.5	13.4			0.0
Koon	AS	4/21/54	10:06 AM	12	4.4	7.8			0.0
Koon	GS	4/21/54	9:30 AM	17	4.4	7.8			4.8
Union	AS	5/1/54	8:45 AM	20	3.5	5.2	2.5		8.7
Yankee	AS	5/7/54	10:19 AM	30	3.2	4.3	1.9	3.4	17.3
Yankee	AS	5/8/54	9:28 AM	6.5	3.1	4.2	1.8	3.1	0.0
Nectar	AS	5/16/54	8:36 AM	4.2	2.7	3.4	1.4	1.7	0.0

[a] AS = Aerial Survey; GS = Ground Survey.

The corrected exposure rate measurements are used in the calculation of $X_{(H+12)}$. Table 5-6 contains the calculated values of $X_{(H+12)}$ that are used in estimating Normalized Deposition for the Castle Series. Normalized Deposition values are converted to units of Bq m^{-2} and decay corrected to 1982. The decay corrected values are converted to soil concentrations Bq kg^{-1} for comparison with measurements.

Table 5-6 Estimates of ^{137}Cs Deposition at Rongelap from the Castle Series.

Test	$X_{(H+12)}$	$\mu Ci\ m^{-2}$	Bq m^{-2}	Decay to 1982	Bq kg^{-1}
Bravo	8369.6	6.5785	243404	127923	581.3
Romeo	814.8	0.6152	22761	11962	54.4
Koon	246.1	0.1858	6875	3613	16.4
Union	131.1	0.0989	3661	1924	8.7
Yankee	91.6	0.0692	2559	1345	6.1
Nectar	0.0	0.0	0.0	0.0	0.0
$\Sigma =$			279760	146768	667

Redwing Series. Only one exposure rate measurement for Rongelap is available during the Redwing Series. The measurement (0.4 mR hr^{-1}) is from a ground survey made by the University of Washington Applied Fisheries Laboratory on 7/24/56. This measurement is approximately 79 hours post-Tewa. Since there are no prior measurements, this net exposure rate from Tewa is assumed to apply to the Redwing Series. The $X_{(H+12)}$ exposure rate from this measurement is 3.5 mR hr^{-1}. This 12-hour exposure rate produced an estimated Normalized Deposition of 2.9E-3 μCi m^{-2} for the Redwing Series. Normalized Deposition values are converted to 108.2 Bq m^{-2} and decay corrected to 1982. The decay corrected values (60 Bq m^{-2}) are converted to soil concentrations (0.3 Bq kg“) for comparison with measurements.

Hardtack I Series. The Public Health Service measured average daily exposure rates on Rongelap. Since these are daily averages. the measurement is assumed to be valid for 12:00 PM local time. This time represents the midpoint of the averaging period (four measurements per day). For the remaining tests in the Hardtack I Series, the exposure rate measurements are corrected for residual exposures from previous tests. These corrections of exposure rate are presented in Table 5-7.

Table 5-7 Corrected Exposure Rate Measurements at Rongelap from Hardtack I Residuals.

Test	Type of Measurement [a]	Local Date	Local Time	Value mR hr^{-1}	Residual Exposure mR hr^{-1} Fir	Koa	Walnut	Oak	Net
Fir	PHSGS	5/14/58	12:00 PM	1.1					1.1
Koa	PHSGS	5/15/58	12:00 PM	1.2	0.7				0.5
Walnut	PHSGS	6/17/58	12:00 PM	0.06	0.04	0.02			0.0
Oak	PHSGS	7/3/58	12:00 PM	0.4	0.02	0.01	0.001		0.4
Poplar	PHSGS	7/16/58	12:00 PM	0.03	0.02	0.01	0.0003	0.064	0.0
Pine	PHSGS	7/29/58	12:00 PM	0.04	0.01	0.01	0.0002	0.032	0.0

[a] PHSGS = Public Health Service Ground Survey.

The corrected exposure rate measurements are used in the calculation of $X_{(H+12)}$. Table 5-8 contains the calculated values of $X_{(H+12)}$ that are used in calculating Normalized Deposition for the Hardtack I Series. Normalized Deposition values are converted to units of Bq m^{-2} and decay corrected to 1982. The decay corrected values are converted to soil concentrations Bq kg^{-1} for comparison with measurements.

Table 5-8 Estimates of ^{137}Cs Deposition at Rongelap from the Hardtack I Series.

Test	$X_{(H+12)}$	μCi m^{-2}	Bq m^{-2}	Decay to 1982	Bq kg“
Fir	6.0	0.0051	187.0	108	0.5
Koa	2.7	0.0023	83.7	48	0.2
Walnut	0.0	0.0	1.2	1	0.00
Oak	4.3	0.0036	133.1	77	0.3
Poplar	0.0	0.0	0.0	0.0	0.0
Pine	0.0	0.0	0.0	0.0	0.0
Σ =			405	233	1.1

The estimated deposition results for Rongelap from the Monte Carlo calculations are presented in Table 5-9. These uncertainty distributions can be divided into percentile estimates of the final results. In this study, the 5th, 25th, 50th, 75th and 95th percentile results are presented from each distribution.

Table 5-9 Distribution Percentiles of Estimated ^{137}Cs Deposition (Bq m^{-2}) on Rongelap.

	Distribution Percentiles				
Operation	5”’	25”	50”	75’”	95’”
Ivy	0.0	0.0	0.0	0.0	0.0
Castle	123835.1	137568.2	146685.4	155818.9	169408.4
Redwing	49.6	55.4	59.5	63.6	69.2
Hardtack I	210.9	223.7	233.2	242.9	256.9

Ronperik

Ivy Series. The aerial survey over Rongerik on 1 1/3/52 detected 0.5 mR hr^{-1} from Ivy Mike. This produced a $X_{(H+12)}$ value of 0.3 mR hr^{-1}. This 12-hour exposure rate produced an estimated Normalized Deposition of 2E-4 $\mu Ci\ m^{-2}$ for the Ivy Series. Normalized Deposition values are converted to 7.5 $Bq\ m^{-2}$ and decay corrected to 1982. The decay corrected values 3.8 $Bq\ m^{-2}$ are converted to soil concentrations 0.02 Bq kg“ for comparison with measurements.

Castle Series. The following table (5-10) presents the calculations of $X_{(H+12)}$ from Castle Bravo. The final measurement in this table (36 $mR\ hr^{-1}$ from an aerial survey on 3/28/54) was not used in the calculation of the average $X_{(H+12)}$ due to the storm that reduced exposure rate readings. However, this value was used in the calculation of residual exposure rate from Castle Bravo while measuring exposure rates for subsequent Castle tests.

Table 5-10 $X_{(H+12)}$ Exposure Rate Calculations Post-Bravo at Rongerik.

Type of Measurement	Local Date	Local Time	$mR\ hr^{-1}$	Hours post	$X_{(H+12)}$
Aerial Survey	3/4/54	2:20 PM	1050	**79.58**	**9203.3**
Ground Survey	3/10/54	**9:ooAM**	**280**	2 18.25	8264.3
Ground Survey	3/17/54	12:00 PM	150	389.25	8882.8
Aerial Survey	3/19/54	5:43 PM	140	142.97	9686.2
Aerial Survey	3/19/54	5:41 AM	80	**142.93**	**5534.5**
Aerial Survey	3/28/54	11:53 AM	36	653.13	3974.4
				Average	83 14.2

For the remaining tests in the Castle Series, the exposure rate measurements are corrected for residual exposures from previous tests. These corrections of exposure rate are presented in Table 5-l 1.

The corrected exposure rate measurements are used in the calculation of $X_{(H+12)}$. Table 5-12 contains the calculated values of $X_{(H+12)}$ that are used in estimating Normalized Deposition for the Castle Series. Normalized Deposition values are converted to units of Bq m^{-2} and decay corrected to 1982. The decay corrected values are converted to soil concentrations Bq kg“ for comparison with measurements.

Table 5-11 Corrected Exposure Rate Measurements at Rongerik from Castle Residuals.

Test	Type of Measurement [a]	Local Date	Local Time	mR hr^{-1}	Residual Exposure mR hr^{-1} Bravo	Romeo	Koon	Yankee	Net
Romeo	AS	3/31/54	10:36 AM	58	31.8				26.2
Koon	AS	4/12/54	11:24 AM	18.6	21.2	5.0			0.0
Koon	AS	4/21/54	10:20 AM	8	16.8	2.9			0.0
Union	AS	5/1/54	8:58 AM	8	13.6	2.0	0.0		0.0
Yankee	AS	5/7/54	10:33 AM	22	12.1	1.6	0.0		8.2
Yankee	AS	5/8/54	9:43 AM	4	11.9	1.6	0.0		0.0
Nectar	AS	5/16/54	8:54 AM	3	10.4	1.3	0.0	1.1	0.0

[a] AS = Aerial Survey.

Table 5-12 Estimates of ^{137}Cs Deposition at Rongerik from the Castle Series.

Test	$X_{(H+12)}$	$\mu Ci\ m^{-2}$	Bq m^{-2}	Decay to 1982	Bq kg^{-1}
Bravo	8314.2	6.5350	241794	127077	584.6
Romeo	307.0	0.23 18	8577	4508	20.7
Koon	0.0	0.0	0.0	0.0	0.0
Union	0.0	0.0	0.0	0.0	0.0
Yankee	44.0	0.0332	1229	646	3.0
Nectar	0.0	0.0	0.0	0.0	0.0
$\Sigma =$			251599	132230	608

Redwing Series. The Public Health Service measured average daily exposure rates on Rongerik. Since these are daily averages the measurements are assumed to be valid for 12:00 PM. This time represents the midpoint of the averaging period (four measurements per day). For the remaining tests in the Redwing Series, the exposure rate measurements are corrected for residual exposures from previous tests. These corrections of exposure rate are presented in Table 5-l 3.

Table 5-13 Corrected Exposure Rate Measurements at Rongerik from Redwing Residuals.

Test	Type of Measurement [a]	Local Date	Local Time	Value mR hr^{-1}	Residual Exposure mR hr^{-1} Zuni	Dakota	Apache	Navajo	Net
Zuni	PHSGS	5/31/56	12:00 PM	0.26					0.26
Dakota	PHSGS	6/28/56	12:00 PM	0.1	0.02				0.08
Apache	PHSGS	7/11/56	12:00 PM	0.1	0.01	0.01			0.08
Navajo	PHSGS	7/13/56	12:00 PM	0.1	0.01	0.01	0.04		0.04
Tewa	PHSGS	7/24/56	12:00 PM	0.4	0.01	0.00	0.01	0.01	0.37

[a] PHSGS = Public Health Service Ground Survey.

The corrected exposure rate measurements are used in the calculation of $X_{(H+12)}$. Table 5-14 contains the calculated values of $X_{(H+12)}$ that are used in calculating Normalized Deposition for the Redwing Series. Normalized Deposition values are converted to units of Bq m^{-2} and decay corrected to 1982. The decay corrected values are converted to soil concentrations Bq kg“ for comparison with measurements.

Table 5-14 Estimates of ^{137}Cs Deposition at Rongerik from the Redwing Series.

Test	$X_{(H+12)}$	µCi m^{-2}	Bq m^{-2}	Decay to 1982	Bq kg-’
Zuni	2.2	0.002	69.3	38	0.2
Dakota	0.4	0.0004	14.1	8	0.0
Apache	0.4	0.0004	13.7	8	0.0
Navajo	0.2	0.0002	7.5	4	0.0
Tewa	3.2	0.0027	101.0	56	0.3
$\Sigma =$			205.6	113.1	0.5

Hardtack I Series. There were no measurements on Rongerik during Hardtack I. Therefore, no ^{137}Cs deposition was estimated on Rongerik from the Hardtack I Series.

The estimated deposition results for Rongerik from the Monte Carlo calculations are presented in Table 5-l 5. These uncertainty distributions can be divided into percentile estimates of the final results. In this study, the 5th, 25th, 50th, 75th and 95th percentile results are presented from each distribution.

Table 5-15 Distribution Percentiles of Estimated ^{137}Cs Deposition (Bq m^{-2}) on Rongerik.

	Distribution Percentiles				
Operation	5th	25'"	50"	75th	95"
Ivy	3.1	3.5	3.8	4.0	4.4
Castle	112844.0	124165.0	132282.4	140421.6	152216.3
Redwing	102.1	108.4	113.0	117.7	124.7

Ujelang

Ivy Series. The aerial survey over Ujelang on 1 1/2/52 detected no exposure rate data for Ivy Mike. Therefore, no ^{137}Cs deposition was estimated on Ujelang from the Ivy Mike test.

Castle Series. The following table (5-16) presents the calculations of $X_{(H+12)}$ from Castle Bravo. The final measurement in this table (0.004 mR hr^{-1} from a fixed monitor on 3/25/54) was not used in the calculation of the average $X_{(H+12)}$ due to the storm that reduced exposure rate readings. However, this value was used in the calculation of residual exposure rate from Castle Bravo while measuring exposure rates for subsequent Castle tests.

Table 5-16 $X_{(H+12)}$ Exposure Rate Calculations Post-Bravo at Ujelang.

Type of Measurement	Local Date	Local Time	mR hr^{-1}	Hours post	$X_{(H+12)}$
Aerial Survey	3/3/54	8:15 AM	0.8	49.50	3.9
Fixed Monitor	3/3/54	6:00 PM	1	59.25	6.0
Fixed Monitor	3/4/54	6:00 PM	0.5	83.25	4.5
Fixed Monitor	3/5/54	6:00 PM	0.2	107.25	2.4
Fixed Monitor	3/25/54	6:00 PM	0.004	587.25	0.4
				Average	4.2

For the remaining tests in the Castle Series, the exposure rate measurements are corrected for residual exposures from previous tests. These corrections of exposure rate are presented in Table 5-I 7.

Table 5-17 Corrected Exposure Rate Measurements at Ujelang from Castle Residuals.

Test	Type of Measure-ment [a]	Local Date	Local Time	mR hr^{-1}	Residual Exposure mR hr^{-1} Bravo	Romeo	Koon	Union	Net
Romeo	FM	3/29/54	12:00 PM	0.14	0.003				0.14
Koon	FM	4/9/54	6:00 AM	0.95	0.002	0.016			0.93
Union	AS	5/2/54	2:50 PM	0.06	0.001	0.005	0.04		0.01
Union	FM	4/27/54	12:00 PM	1.3	0.001	0.006	0.06		1.24
Yankee	FM	5/8/54	6:00 AM	1.5	0.001	0.004	0.03	0.04	1.42
Nectar	FM	---[b]	---	---	---	---	---	---	0.0

[a] AS = Aerial Survey; FM = Fixed Monitor;
[b] no measurement.

The corrected exposure rate measurements are used in the calculation of $X_{(H+12)}$. Table 5-l 8 contains the calculated values of $X_{(H+12)}$ that are used in estimating Normalized Deposition for the Castle Series. Normalized Deposition values are converted to units of Bq m^{-2} and decay corrected to 1982. The decay corrected values are converted to soil concentrations Bq kg^{-1} for comparison with measurements,

Table 5-18 Estimates of ^{137}Cs Deposition at Ujelang from the Castle Series.

Test	$X_{(H+12)}$	μCi m^{-2}	Bq m^{-2}	Decay to 1982	Bq kg-’
Bravo	4.2	0.003	122	64	0.25
Romeo	0.7	0.001	21	11	0.04
Koon	4.4	0.003	124	65	0.26
Union	1.8	0.001	50	26	0.10
Yankee	11.1	0.008	311	163	0.65
Nectar	0.0	0.0	0.0	0.0	0.0
Σ =			627.5	329.8	1.3

Redwing Series. The Public Health Service measured average daily exposure rates on Ujelang. Since these are daily averages, the measurements are assumed to be valid for 12:00 PM. This time represents the midpoint of the averaging period (four measurements per day). For the remaining tests in the Redwing Series, the exposure rate measurements are corrected for residual exposures from previous tests. These corrections of exposure rate are presented in Table 5- 19.

Table 5-19 Corrected Exposure Rate Measurements at Ujelang from Redwing Residuals.

Test	Type of Measurement [a]	Local Date	Local Time	Value $mR\ hr^{-1}$	Residual Exposure $mR\ hr^{-1}$ Zuni	Dakota	Apache	Navajo	Net
Zuni	PHSGS	6/1/56	12:00 PM	0.23					0.23
Dakota	PHSGS	6/28/56	12:00 PM	0.07	0.022				0.05
Apache	PHSGS	7/11/56	12:00 PM	0.05	0.015	0.005			0.03
Navajo	PHSGS	7/14/56	12:00 PM	0.045	0.014	0.004	0.011		0.02
Tewa	PHSGS	7/23/56	12:00 PM	1.5	0.011	0.003	0.003	0.003	1.48

[a] PHSGS = Public Health Service Ground Survey.

The corrected exposure rate measurements are used in the calculation of $X_{(H+12)}$. Table 5-20 contains the calculated values of $X_{(H+12)}$ that are used in calculating Normalized Deposition for the Redwing Series. Normalized Deposition values are converted to units of Bq m^{-2} and decay corrected to 1982. The decay corrected values are converted to soil concentrations Bq kg^{-1} for comparison with measurements.

Table 5-20 Estimates of ^{137}Cs Deposition at Ujelang from the Redwing Series.

Test	$X_{(H+12)}$	$\mu Ci\ m^{-2}$	Bq m^{-2}	Decay to 1982	Bq kg^{-1}
Zuni	3	0.002	84	46	0.18
Dakota	0.3	0.0002	8.3	5	0.02
Apache	0.2	0.0001	5.2	3	0.01
Navajo	0.1	0.0001	4.3	2	0.01
Tewa	8	0.007	256	141	0.56
$\Sigma =$			358.1	197.1	0.8

Hardtack I Series. The Public Health Service measured average daily exposure rates on Ujelang. Since these are daily averages, the measurements are assumed to be valid for 12:00 PM. This time represents the midpoint of the averaging period (four measurements per day). For the remaining tests in the Hardtack I Series, the exposure rate measurements are corrected for residual exposures from previous tests. These corrections of exposure rate are presented in Table 5-21.

Table 5-21 Corrected Exposure Rate Measurements at Ujelang from Hardtack I Residuals.

Test	Type of Measurement [a]	Local Date	Local Time	Value $mR\ hr^{-1}$	Residual Exposure $mR\ hr^{-1}$ Fir	Koa	Walnut	Oak	Net
Fir	PHSGS	5/14/58	12:00 PM	0.22					0.22
Koa	PHSGS	5/16/58	12:00 PM	0.27	0.10				0.17
Walnut	PHSGS	6/18/58	12:00 PM	0.06	0.007	0.009			0.04
Oak	PHSGS	7/4/58	12:00 PM	0.18	0.004	0.006	0.005		0.17
Poplar	PHSGS	7/17/58	12:00 PM	0.06	0.003	0.004	0.003	0.04	0.01
Pine	PHSGS	7/30/58	12:00 PM	0.05	0.003	0.003	0.002	0.02	0.02

[a] PHSGS = Public Health Service Ground Survey.

The corrected exposure rate measurements are used in the calculation of $X_{(H+12)}$. Table 5-22 contains the calculated values of $X_{(H+12)}$ that are used in calculating Normalized Deposition for the Hardtack I Series. Normalized Deposition values are converted to units of Bq m^{-2} and decay corrected to 1982. The decay corrected values are converted to soil concentrations Bq kg“ for comparison with measurements.

The estimated deposition results for Ujelang from the Monte Carlo calculations are presented in Table 5-23. These uncertainty distributions can be divided into percentile estimates of the final results. In this study, the 5th, 25th, 50th, 75th and 95th percentile results are presented from each distribution.

Table 5-22 Estimates of ^{137}Cs Deposition at Ujelang from the Hardtack I Series.

Test	$X_{(H+12)}$	$\mu Ci\ m^{-2}$	$Bq\ m^{-2}$	Decay to 1982	$Bq\ kg^{-1}$
Fir	1	0.001	37	22	0.09
Koa	1	0.001	45	26	0.10
Walnut	0.4	0.0003	12	7	0.03
Oak	3	0.002	78	45	0.18
Poplar	0.2	0.0001	4.8	3	0.01
Pine	0.2	0.0002	6.1	4	0.01
Σ =			183.0	105.4	0.4

Table 5-23 Distribution Percentiles of Estimated ^{137}Cs Deposition ($Bq\ m^{-2}$) on Ujelang.

	Distribution Percentiles				
Operation	5th	25"	50"	75th	95th
Ivy	0.0	0.0	0.0	0.0	0.0
Castle	298.6	317.1	330.2	343.3	360.3
Redwing	172.6	186.7	196.6	206.7	221.5
Hardtack I	96.3	101.8	105.5	109.2	114.5

Utirik

Ivy Series. The aerial survey over Utirik on 1 1/3/52 detected 0.2 mR hr-1 from Ivy Mike. This produced a $X_{(H+12)}$ value of 1.1 $mR\ hr^{-1}$. This 12-hour exposure rate produced an estimated Normalized Deposition of 8E-4 $\mu Ci\ m^{-2}$ for the Ivy Series. Normalized Deposition values are converted to 30 $Bq\ m^{-2}$ and decay corrected to 1982. The decay corrected values 15.1 $Bq\ m^{-2}$ are converted to soil concentrations 0.07 $Bq\ kg^{-1}$ for comparison with measurements.

Castle Series. The following table (5-24) presents the calculations of $X_{(H+12)}$ from Castle Bravo. The final measurement in this table (0 $mR\ hr^{-1}$ from an aerial survey on 3/28/54) was not used in the calculation of the average $X_{(H+12)}$ due to the storm that reduced exposure rate readings. However, this zero value means that there was no residual exposure rate from Castle Bravo for subsequent Castle tests.

Table 5-24 $X_{(H+12)}$ Exposure Rate Calculations Post-Bravo at Utirik.

Type of Measurement	Local Date	Local Time	mR hr^{-1}	Hours post	$X_{(H+12)}$
Aerial Survey	3/4/54	4:55 PM	48	82.17	437.2
Aerial Survey	3/19/54	7:13 PM	12	444.47	833.6
Ground Survey	3/3/54	1:45 PM	160	55.00	899.0
Ground Survey	3/4/54	9:15 AM	120	74.50	971.5
Ground Survey	3/9/54	9:00 AM	40	194.25	1026.2
Aerial Survey	3/28/54	2:33 PM	0	655.80	0.0
				Average	833.5

For the remaining tests in the Castle Series, the exposure rate measurements are corrected for residual exposures from previous tests. These corrections of exposure rate are presented in Table 5-25.

Table 5-25 Corrected Exposure Rate Measurements at Utirik from Castle Residuals.

Test	Type of Measure-ment [a]	Local Date	Local Time	mR hr^{-1}	Residual Exposure mR hr^{-1} Bravo	Romeo	Koon	Yankee	Net
Romeo	AS	3/31/54	12:20 PM	6.8	0.0				6.8
Koon	AS	4/12/54	2:15 PM	3.8	0.0	1.3			2.5
Koon	AS	4/21/54	12:59 PM	0.8	0.0	0.8			0.02
Koon	GS	4/23/54	11:00 AM	3	0.0	0.7			2.3
Koon	GS	4/23/54	11:00 AM	2.8	0.0	0.7			2.1
Koon	GS	4/23/54	11:00 AM	2.2	0.0	0.7			1.5
Union	AS	5/1/54	11:35 AM	1.7	0.0	0.5	0.8		0.4
Yankee	AS	5/7/54	1:18 PM	6	0.0	0.4	0.6		5.0
Yankee	AS	5/8/54	12:23 PM	1.2	0.0	0.4	0.6		0.2
Nectar	AS	5/16/54	11:24 AM	0.8	0.0	0.3	0.4	0.0	0.0

[a] AS = Aerial Survey; GS = Ground Survey.

The corrected exposure rate measurements are used in the calculation of $X_{(H+12)}$. Table 5-26 contains the calculated values of $X_{(H+12)}$ that are used in estimating Normalized Deposition for the Castle Series. Normalized Deposition values are converted to units of Bq m^{-2} and decay corrected to 1982. The decay corrected values are converted to soil concentrations Bq kg^{-1} for comparison with measurements.

Table 5-26 Estimates of ^{137}Cs Deposition at Utirik from the Castle Series.

Test	$X_{(H+12)}$	$\mu Ci\ m^{-2}$	$Bq\ m^{-2}$	Decay to 1982	$Bq\ kg^{-1}$
Bravo	833.5	0.6551	21240	12740	60.0
Romeo	81.4	0.0615	2274	1195	5.6
Koon	79.6	0.0601	2223	1168	5.5
Union	5.9	0.0044	164	86	0.4
Yankee	14.9	0.0113	417	219	1.0
Nectar	0.0	0.0	0.0	0.0	0.0
$\Sigma =$			29318	15408	72.5

<u>Redwing Series</u>. The Public Health Service measured average daily exposure rates on Utirik. Since these are daily averages, the measurements are assumed to be valid for 12:00 PM. This time represents the midpoint of the averaging period (four measurements per day). For the remaining tests in the Redwing Series, the exposure rate measurements are corrected for residual exposures from previous tests. These corrections of exposure rate are presented in Table 5-27.

Table 5-27 Corrected Exposure Rate Measurements at Utirik from Redwing Residuals.

Test	Type of Measurement [a]	Local Date	Local Time	Value $mR\ hr^{-1}$	Residual Exposure $mR\ hr^{-1}$ Zuni	Dakota	Apache	Navajo	Net
Zuni	PHSGS	5/31/56	12:00 PM	0.26					0.3
Dakota	PHSGS	6/29/56	12:00 PM	0.15	0.02				0.1
Apache	PHSGS	7/13/56	12:00 PM	0.05	0.01	0.019			0.02
Navajo	PHSGS	7/16/56	12:00 PM	0.05	0.01	0.015	0.011		0.01
Tewa	PHSGS	7/22/56	12:00 PM	0.04	0.009	0.011	0.005	0.005	0.01

[a] PHSGS = Public Health Service Ground Survey.

The corrected exposure rate measurements are used in the calculation of $X_{(H+12)}$. Table 5-28 contains the calculated values of $X_{(H+12)}$ that are used in calculating Normalized Deposition for the Reduing Series. Normalized Deposition values are converted to units of Bq m^{-2} and decay corrected to 1982. The decay corrected values are converted to soil concentrations Bq kg^{-1} for comparison with measurements.

Table 5-28 Estimates of ^{137}Cs Deposition at Utirik from the Redwing Series.

Test	$X_{(H+12)}$	$\mu Ci\ m^{-2}$	$Bq\ m^{-2}$	Decay to 1982	$Bq\ kg^{-1}$
Zuni	2.2	0.002	69.3	38	0.18
Dakota	1.1	0.001	35.2	19	0.09
Apache	0.2	0.0	7.3	4	0.02
Navajo	0.2	0.0	6.2	3	0.02
Tewa	0.0	0.0	0.7	0.0	0.0
$\Sigma =$			118.7	65.3	0.3

Hardtack I Series. The Public Health Service measured average daily exposure rates on Utirik. Since these are daily averages, the measurements are assumed to be valid for 12:00 PM. This time represents the midpoint of the averaging period (four measurements per day). For the remaining tests in the Hardtack I Series, the exposure rate measurements are corrected for residual exposures from previous tests. These corrections of exposure rate are presented in Table 5-29.

Table 5-29 Corrected Exposure Rate Measurements at Utirik from Hardtack I Residuals.

Test	Type of Measurement [a]	Local Date	Local Time	Value $mR\ hr^{-1}$	Residual Exposure $mR\ hr^{-1}$ Fir	Koa	Walnut	Oak	Net
Fir	PHSGS	5/14/58	12:00 PM	1					1.0
Koa	PHSGS	5/16/58	12:00 PM	0.75	0.46				0.3
Walnut	PHSGS	6/20/58	12:00 PM	0.05	0.03	0.01			0.01
Oak	PHSGS	7/2/58	12:00 PM	0.04	0.02	0.01	0.001		0.01
Poplar	PHSGS	7/17/58	12:00 PM	0.07	0.02	0.01	0.001	0.001	0.05
Pine	PHSGS	7/29/58	12:00 PM	0.04	0.01	0.01	0.000	0.008	0.01

[a] PHSGS = Public Health Service Ground Survey.

The corrected exposure rate measurements are used in the calculation of $X_{(H+12)}$. Table 5-30 contains the calculated values of $X_{(H+12)}$ that are used in calculating Normalized Deposition for the Hardtack I Series. Normalized Deposition values are converted to units of Bq m^{-2} and decay corrected to 1982. The decay corrected values are converted to soil concentrations Bq kg^{-1} for comparison with measurements.

Table 5-30 Estimates of ^{137}Cs Deposition at Utirik from the Hardtack I Series.

Test	$X_{(H+12)}$	$\mu Ci\ m^{-2}$	Bq m^{-2}	Decay to 1982	Bq kg-'
Fir	5.5	0.0046	170.0	98	0.46
Koa	2.5	0.0021	77.2	44	0.21
Walnut	0.1	0.0001	3.0	2	0.01
Oak	0.1	0.0001	1.9	1	0.01
Poplar	0.5	0.0004	15.0	9	0.04
Pine	0.1	0.0001	2.1	1	0.01
$\Sigma =$			269.2	155.1	0.7

The estimated deposition results for Utirik from the Monte Carlo calculations are presented in Table 5-3 1. These uncertainty distributions can be divided into percentile estimates of the final results. In this study, the 5^{th}, 25^{th}, 50^{th}, 75^{th} and 95^{th} percentile results are presented from each distribution.

Table 5-3 1 Distribution Percentiles of Estimated ^{137}Cs Deposition (Bq m^{-2}) on Utirik.

	Distribution Percentiles				
Operation	5th	25th	50th	75th	95th
Ivy	8.9	12.5	15.1	17.6	21.3
Castle	13902.9	14802.0	15448.8	16067.5	16960.2
Redwing	59.1	62.7	65.3	67.8	71.6
Hardtack I	138.7	148.5	155.1	162.1	172.3

Wotho

Ivy Series, The aerial survey over Wotho on 1 1/3/52 detected 0.1 mR hr-1 from Ivy Mike. This produced a $X_{(H+12)}$ value of 0.5 mR hr- 1. This 12-hour exposure rate produced an estimated Normalized Deposition of 4E-4 μCi m^{-2} for the Ivy Series. Normalized Deposition values are converted to 15 Bq m^{-2} and decay corrected to 1982.

The decay corrected values 7.5 Bq m^{-2} are converted to soil concentrations 0.04 Bq kg“ for comparison with measurements.

Castle Series. The following table (5-32) presents the calculations of $X_{(H+12)}$ from Castle Bravo. The final measurement (0 mR hr^{-1} from an aerial survey on 3/28/54) was not used in the calculation of the average $X_{(H+12)}$ due to the storm that reduced exposure rate readings. However, this zero value means that there was no residual exposure rate from Castle Bravo for subsequent Castle tests.

Table 5-32 $X_{(H+12)}$ Exposure Rate Calculations Post-Bravo at Wotho.

Type of Measurement	Local Date	Local Time	mR hr^{-1}	Hours post	$X_{(H+12)}$
Aerial Survey	3/4/54	8:14 AM	1.6	73.48	12.7
Aerial Survey	3/4/54	8:19 AM	1.6	73.57	12.8
Aerial Survey	3/4/54	8:20 AM	0.8	73.58	6.4
Ground Survey	3/6/54	4:15 PM	0.8	129.50	12.6
Aerial Survey	3/19/54	4:43 PM	0.05	441.97	3.4
Aerial Survey	3/19/54	4:48 PM	0.03	442.05	2.1
Aerial Survey	3/19/54	4:49 PM	0.05	442.07	3.5
				Average	7.6

For the remaining tests in the Castle Series, the exposure rate measurements are corrected for residual exposures from previous tests. These corrections of exposure rate are presented in Table 5-33.

Table 5-33 Corrected Exposure Rate Measurements at Wotho from Castle Residuals.

Test	Type of Measure-ment [a]	Local Date	Local Time	mR hr^{-1}	Residual Exposure mR hr^{-1} Bravo	Romeo	Koon	Yankee	Net
Romeo	AS	3/31 54	9:10 AM	1.7	0.03				1.7
Koon	AS	4/12/54	9:59 AM	0.2	0.02	0.3			0.0
Union	AS	5/1 54	7:37 AM	0.3	0.01	0.12	0.0		0.2
Yankee	AS	5/7/54	8:57 AM	1.6	0.01	0.10	0.0		1.5
Yankee	AS	5/8/54	8:10 AM	0.2	0.01	0.10	0.0		0.1
Nectar	AS	5/16/54	7:22 AM	0.08	0.01	0.08	0.0	0.11	0.0

[a] AS = Aerial Survey; GS = Ground Survey.

The corrected exposure rate measurements are used in the calculation of $X_{(H+12)}$. Table 5-34 contains the calculated values of $X_{(H+12)}$ that are used in estimating Normalized Deposition for the Castle Series. Normalized Deposition values are converted to units of Bq m^{-2} and decay corrected to 1982. The decay corrected values are converted to soil concentrations Bq kg^{-1} for comparison with measurements.

Table 5-34 Estimates of ^{137}Cs Deposition at Wotho from the Castle Series.

Test	$X_{(H+12)}$	$\mu Ci\ m^{-2}$	Bq m^{-2}	Decay to 1982	Bq kg^{-1}
Bravo	7.6	0.0060	222	117	0.6
Romeo	19.3	0.0145	538	283	1.4
Koon	0.0	0.0	0.0	0.0	0.0
Union	2.4	0.0018	68	36	0.2
Yankee	4.2	0.0032	117	62	0.3
Nectar	0.0	0.0	0.0	0.0	0.0
$\Sigma =$			945.4	496.9	2.4

Redwing Series. The Public Health Service measured average daily exposure rates on Wotho. Since these are daily averages, the measurements are assumed to be valid for 12:00 PM. This time represents the midpoint of the averaging period (four measurements per day). For the remaining tests in the Redwing Series, the exposure rate measurements are corrected for residual exposures from previous tests. These corrections of exposure rate are presented in Table 5-35.

The corrected exposure rate measurements are used in the calculation of $X_{(H+12)}$. Table 5-36 contains the calculated values of $X_{(H+12)}$ that are used in calculating Normalized Deposition for the Redwing Series. Normalized Deposition values are corn-erted to units of Bq m^{-2} and decay corrected to 1982. The decay corrected values are converted to soil concentrations Bq kg^{-1} for comparison with measurements.

Table 5-35 Corrected Exposure Rate Measurements at Wotho from Redwing Residuals.

Test	Type of Measurement [a]	Local Date	Local Time	Value mR hr^{-1}	Residual Exposure mR hr^{-1} Zuni	Dakota	Apache	Navajo	Net
Zuni	PHSGS	5/30/56	12:00 PM	4.5					4.5
Dakota	PHSGS	6/28/56	12:00 PM	0.25	0.20				0.05
Apache	PHSGS	7/12/56	12:00 PM	0.12	0.13	0.0			0.0
Navajo	PHSGS	7/14/56	12:00 PM	0.1	0.13	0.0	0.0		0.0
Tewa	PHSGS	7/22/56	12:00 PM	0.08	0.10	0.0	0.0	0.0	0.0

[a] PHSGS = Public Health Service Ground Survey.

Table 5-36 Estimates of ^{137}Cs Deposition at Wotho from the Redwing Series.

Test	$X_{(H+12)}$	μCi m^{-2}	Bq m^{-2}	Decay to 1982	Bq kg-’
Zuni	25	0.021	778.3	428	2.1
Dakota	0	0.0	7.9	4	0.0
Apache	0	0.0	0.0	0	0.0
Navajo	0	0.0	0.0	0	0.0
Tewa	0	0.0	0.0	0	0.0
Σ =			786.2	432.6	2.1

Hardtack I Series. The Public Health Service measured average daily exposure rates on Wotho. Since these are daily averages, the measurements are assumed to be valid for 12:OO PM. This time represents the midpoint of the averaging period (four measurements per day). For the remaining tests in the Hardtack I Series, the exposure rate measurements are corrected for residual exposures from previous tests. These corrections of exposure rate are presented in Table 5-37.

The corrected exposure rate measurements are used in the calculation of $X_{(H+12)}$. Table 5-38 contains the calculated values of $X_{(H+12)}$ that are used in calculating Normalized Deposition for the Hardtack I Series. Normalized Deposition values are converted to units of Bq m^{-2} and decay corrected to 1982. The decay corrected values are converted to soil concentrations Bq kg^{-1} for comparison with measurements.

Table 5-37 Corrected Exposure Rate Measurements at Wotho from Hardtack I Residuals.

Test	Type of Measure-ment [a]	Local Date	Local Time	Value mR hr^{-1}	Residual Exposure mR hr^{-1} Fir	Koa	Walnut	Oak	Net
Fir	PHSGS	5/15/58	12:00 PM	0.16					0.2
Koa	PHSGS	5/16/58	12:00 PM	0.23	0.12				0.1
Walnut	PHSGS	6/17/58	12:00 PM	0.02	0.01	0.01			0.01
Oak	PHSGS	7/3/58	12:00 PM	1	0.01	0.004	0.0004		1.0
Poplar	PHSGS	7/18/58	12:00 PM	0.09	0.004	0.003	0.0002	0.152	0.0
Pine	PHSGS	7/31/58	12:00 PM	0.05	0.003	0.002	0.0001	0.08	0.0

[a] PHSGS = Public Health Service Ground *Survey*.

Table 5-38 Estimates of ^{137}Cs Deposition at Wotho from the Hardtack I Series.

Test	$X_{(H+12)}$	µCi m^{-2}	Bq m^{-2}	Decay to 1982	Bq kg-’
Fir	1	0.0012	42.7	25	0.1
Koa	1	0.0008	30.4	17	0.1
Walnut	0.0	0.0	1.0	1	0.0
Oak	12	0.0097	360.4	208	1.0
Poplar	0	0.0	0.0	0	0.0
Pine	0.0	0.0	0.0	0	0.00
Σ =			434.5	250.3	1.2

The estimated deposition results for Wotho from the Monte Carlo calculations are presented in Table 5-39. These uncertainty distributions can be divided into percentile estimates of the final results. In this study, the 5th, 25th, 50th, 75th and 95th percentile results are presented from each distribution.

Table 5-39 Distribution Percentiles of Estimated ^{137}Cs Deposition (Bq m^{-2}) on Wotho.

Operation	Distribution Percentiles 5th	25”’	50th	75”’	95”
Ivy	4.4	6.2	7.5	8.7	10.6
Castle	392.0	451.4	496.4	541.9	606.1
Redwing	366.0	404.1	43 1.8	459.6	500.5
Hardtack I	215.7	236.1	250.5	264.5	285.6

Calculations Based on Gummed Film Data

This section discusses the calculations performed using gummed film data. The atolls for which deposition is estimated from gummed film information include Kwajalein and Majuro. Since the gummed film measurements detected minute concentrations of fallout from shots less than one megaton, calculations are not restricted to tests greater than one megaton. Calculations for each atoll are segregated by test series. Deposition estimates for each test within the series are summed to produce a series total.

Kwajalein

Gross beta activity measurements were reported for duplicate gummed film collectors. The duplicate averages were decay corrected to the mid-point of the sampling date using Decay Factor formulations discussed in the Methods Section. The decay corrected values were then subjected to an efficiency correction calculation. The efficiencies, as a function of precipitation, were obtained from Table 3-1 1. The resultant total depositions were converted to ^{137}Cs deposition. The ^{137}Cs depositions were summed by shot, series, and all test shots within the Castle, Redwing, and Hardtack I Series.

Ivy Series. The gummed film method calculations produced an estimated median decay corrected deposition of 14.5 Bq m^{-2} at Kwajalein from the Ivy Series.

Castle Series. Several data gaps exist in the gummed film measurements from Castle Bravo, Romeo and Yankee. To reconstruct this data, exposure rate measurements made just after each test are used. The HASL performed data comparisons using gummed film and aerial surveys. From this comparison and literature values they estimated that approximately 1 mR hr^{-1} equates to 400,000 dpm ft^{-2} (handwritten data sheets obtained from EML). This relationship was used in the estimates of missing gummed film deposition data. Table 5-40 gives the results of this data reconstruction using exposure rate measurements.

Table 5-40 Reconstructed Missing Gummed Film Deposition Data with Exposure Rate Measurements.

Date	mR hr^{-1}	dpm ft^{-2}
Bravo		
3/2/54	0.02	6000
3/3/54	0.08	33000
3/4/54	0.19	76900
3/5/54	0.12	49000
3/6/54	0.15	61000
3/7/54	0.35	140000
3/8/54	0.41	164000
3/9/54	0.23	92000
3/10/54	0.30	118000
Romeo		
3/29/54	0.05	20000
3/30/54	0.22	87500
3/31/54	0.73	290000
4/1/54	1.70	680000
4/2/54	1.00	400000
4/3/54	0.93	370000
Yankee		
5/6/54	0.55	220000
5/7/54	3.50	1400000
5/8/54	2.55	1020000

The estimated deposition results for Kwajalein from the Monte Carlo calculations are presented in Table 5-41. These uncertainty distributions can be divided into percentile estimates of the final results. In this study, the 5th, 25th, 50th, 75th and 95th percentile results are presented from each distribution.

Table 5-4 1 Distribution Percentiles of Estimated ^{137}Cs Deposition (Bq m^{-2}) on Kwajalein.

Operation	Distribution Percentiles 5”’	25th	50”	75th	95”’
Ivy	5.10	6.40	7.31	8.22	9.52
Castle	443.16	467.80	489.48	511.33	540.32
Redwing	778.66	843.05	890.68	937.14	1005.03
Hardtack I	186.97	200.79	216.66	235.01	256.37

Majuro

The estimated deposition results for Majuro from the Monte Carlo calculations are presented in Table 5-42. These uncertainty distributions can be divided into percentile estimates of the final results. In this study, the 5^{th}, 25^{th}, 50^{th}, 75^{th} and 95^{th} percentile results are presented from each distribution.

Table 5-42 Distribution Percentiles of Estimated ^{137}Cs Deposition (Bq m^{-2}) on Majuro.

Operation	Distribution Percentiles 5”’	25’”	50”	75’”	95th
Ivy	2.10	2.85	3.38	3.92	4.69
Castle	152.27	165.56	180.54	199.00	220.17

Calculations of Arc-Distance

The calculations of arc-distance were performed in spreadsheets with Microsoft Excel formulas. The calculations performed here are described in the Methods Section under spatial analysis. Table 5-43 presents the average arc-distance for each atoll in the RMI.

Table 5-43 Average Arc-Distances (km) by Atoll from Bikini Atoll.

Atoll	Arc-distance	Atoll	Arc-distance
Ailinginae	283	Lib	1116
Ailinglaplap	1478	Likiep	932
Ailuk	978	Majuro	1802
Amo	1899	Maloelap	1475
Aur	1563	Mejit	1144
Bikar	786	Mili	2150
Bikini	49	Namorik	1985
Ebon	2317	Namu	1272
Enewetak	1522	Rongelap	334
Erikub	1213	Rongerik	416
Jabat	1417	Taka	814
Jaluit	1927	Taongi	466
Jemo	958	Ujae	864
Kili	2045	Uj elang	2217
Knox	2218	Utirik	832
Kwajalein	894	Wotho	512
Lae	901	Wotje	1155

Statistical Analysis of ^{137}Cs Concentrations

In order to evaluate ^{137}Cs concentrations in soil, it is important to understand the translocation of cesium in the soil column. Information from the World Health Organization (WHO) is summarized in the following paragraph.

Cesium is strongly fixed in most soils. Therefore, downward migration in the soil profile is reduced. The movement of ^{137}Cs is appreciably less than that of ^{90}Sr in mineral soils. Three to four years after deposition on the soil surface, the median depth of vertical soil migration is usually less than 2 cm. Its mobility may be increased somewhat in organic soils (WHO 1983). Because of this low mobility, the analyses will concentrate on the 0- 15 cm layer.

The first analysis included a summation and averaging of ^{137}Cs in the 15 cm depth for each atoll. Cesium-137 concentrations in the O-5, 5-l 0, and 10-l 5 cm depth increments were summed to produce the total ^{137}Cs concentration in the 0-15 cm depth. These 15 cm totals were then decay corrected to 1982 (the final year of major fallout from global sources, UNSCEAR 1993). These decay-corrected soil profile totals were then averaged across the Atoll. The calculated 0-15 cm ^{137}Cs concentrations (Bq kg^{-1}) are given in Table 5-44.

Table 5-44 Calculated ^{137}Cs Concentrations in the 0-15 cm Depth for Selected Atolls.

	^{137}Cs Concentrations, Bq kg^{-1}					
Atoll	Arithmetic Mean	Stdev	Geo-Mean	GSD	Max	Min
Kwajalein	9.1	7.5	6.62	2.52	26.3	1.2
Majuro	3.2	1.9	2.55	2.11	6.2	0.7
Rongelap[a]	678.8	386.2	630.7	1.50	1183.9	362.4
Rongerik	618.1	399.8	498.4	2.11	1464.5	151.9
Ujelang	18.8	13.1	13.6	2.64	32.6	3.4
Utirik	94.3	84.4	64.5	2.75	209.7	18.6
Wotho	10.7	6.5	8.92	2.28	15.8	3.5

[a] Calculations for Rongelap only include data from Rongelap Islet, Rongelap Atoll.

In this table, calculations for Rongelap Atoll only include data from Rongelap Islet. This islet was the location of the village and population eventually evacuated from Rongelap. This data censoring is necessary because of the large gradient of historical exposure rate measurements and contemporary soil concentrations from the northern and southern portions of Rongelap Atoll. For example, historical exposure rate measurements post-Bravo were approximately 40 times higher in the north side of Rongelap Atoll versus the south side. Contemporary soil concentrations also demonstrate this large gradient. In addition, the PHS took exposure rate measurements only at Rongelap Islet during later test operations.

Similar calculations were performed on data from all atolls within the RMI. A plot of this resultant data reveals an inverse relationship in soil concentrations with direction and distance (arc-distance) as seen in Figure 5-2. The lower and upper estimate lines in this figure represent the 5^{th} and 95" percentile range of the global fallout estimates calculated and discussed in Chapter 6.

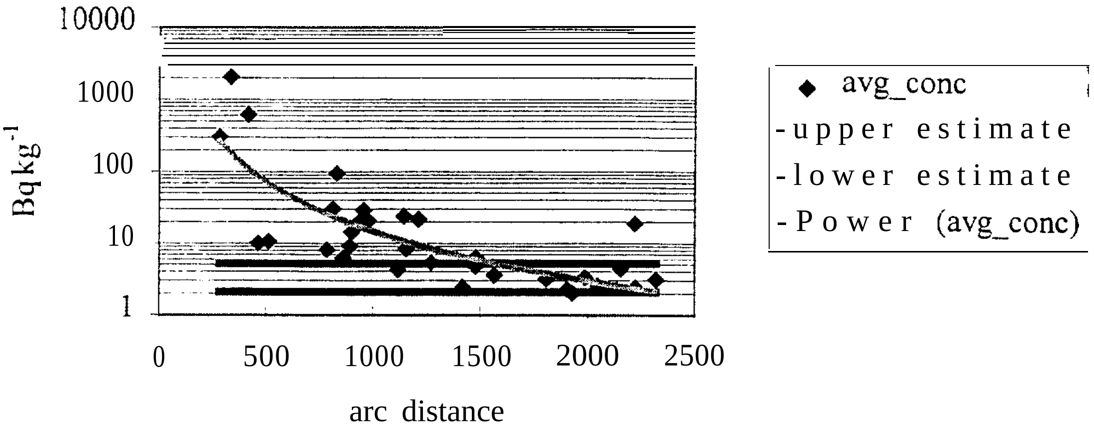

Figure 5-2 Cs- 137 Soil Concentration with Arc-Distance from Bikini.

The second analysis was estimating the fraction of Cs residing in the O-1 5 cm depth increment. The fractions were obtained by the quotient of the summed values from the first analysis and the total activity in the O-30 cm layer. The resultant fractions for the atolls are given in Table 5-45. The average fraction for the entire data set was 0.76.

Table 5-45 Fraction of ^{137}Cs Residing in the O-15 cm Soil Layer.

Atoll	Fraction	Atoll	Fraction
Ailinginae	0.79	Lib	0.48
Ailinglaplap	0.82	Likiep	0.83
Ailuk	0.86	Majuro	0.71
Amo	0.82	Maloelap	0.78
Aur	0.70	Mejit	0.83
Bikar	0.61	Mili	0.74
Bikini	0.60	Narnorik	0.76
Ebon	0.82	Namu	0.79
Enewetak	0.69	Rongelap	0.82
Erikub	0.86	Rongerik	0.83
Jabat	0.76	Taka	0.72
Jaluit	0.77	Taongi	0.67
Jemo	0.89	Ujae	0.81
Kili	1.00	Ujelang	0.71
Knox	0.76	Utirik	0.85
Kwajalein	0.72	Wotho	0.86
Lae	0.83	Wotje	0.83
		Overall Average	0.76

CHAPTER 6
VALIDATION

Introduction

This chapter presents the validation procedures and results for several Atolls in the Marshall Islands. Validation is the comparison of measured (or observed) environmental concentrations with predicted concentrations. Contemporary soil measurements from the Nationwide Radiological Survey are used as the observed data set in this validation. The validation output includes ratios of predictions to observations (P/O) and a discussion of method (or model) bias.

Comparisons of Estimates

There are several different ways to compare predicted and observed concentrations. One way is to view and compare the data graphically. Another way is to express the predictions and observations as ratios. These P/O ratios can be expressed as bias; where:

$P/O = 1$ means an exact agreement;

$P/O > 1$ means there is an over-prediction; and

$P/O < 1$ means there is an under-prediction.

Geometric bias is used when data is compared spatially or temporally. This geometric bias (also known as the geometric mean) of individual P/O ratios is given by the following equation:

$$\text{Geometric bias} = \exp\left(\frac{\sum_i \ln(P_i / O_i)}{n}\right)$$

where

P_i = predicted concentration at location i;

O_i = observed concentration at location i; and

n = number of locations.

If predictions are within a factor of two of observations (e.g., geometric bias of 0.5 to 2), the methods (or models) are considered good. This factor of two comes from comparisons of P/O air concentrations with the typical Gaussian plume atmospheric dispersion model as described by Miller and Hively (1987). In their analyses, a factor of two was found for distances within 10 km and a factor of four (0.25 to 4) was observed for distances between 10 and 150 km.

Global Fallout Estimates

The estimates of global fallout in the Marshall Islands cannot be validated directly. They can, however, be compared to estimates made by various researchers. This corroboration can lend credibility to estimates in this project. The following discussion presents global fallout estimates made by various organizations in the Marshall Islands, A comparison of the estimates with those of other researchers at the end of this discussion shows good agreement.

Simon (1997) estimated "presently" that between 400 and 800 Bq m^{-2} of ^{137}Cs were deposited in the Marshall Islands from global sources. Therefore, these values are considered a current estimate as of 1992. To compare this estimate with methods of this project. values must first be decay corrected to 1982. Accounting for this 1 O-year decay time adjusts the estimated range to 503 and 1007 Bq m^{-2}. The median estimate from this range is 755 Bq m^{-2}. In a summary report to the government of the Republic of the Marshall Islands (RMI 1994) Simon also reports a value of 500 Bq m^{-2}.

Musolino (1997) used soil concentrations at Majuro and Mili Atolls as measured by Greenhouse and Hamilton for a background estimate. Fifty-four samples collected from the O-l 5 cm depth in 1988 produced an average ^{137}Cs concentration of 3.9 ± 2.0 Bq kg-‘. Decay correcting this value back to 1982 produces an activity concentration of 4.5 Bq kg-‘. To compare this estimate with others, Bq kg^{-1} is converted to Bq m^{-2} using the equation previously discussed in the Methods Section. The results of this conversion show a median estimate of 806 Bq m^{-2} with 95% confidence interval of 413 and 1198 Bq m^{-2} respectively.

The Lawrence Berkley Laboratory (LBL) performed an intercomparison of background levels of radioactivity in Micronesia in 1977 (Greenhouse and Meltenberger 198 1). Their estimate of background was 2.1 pCi m^{-2} in 1977. Conversion of this value to comparable units (777 Bq m^{-2}) and to 1982 levels results in a value of 693 Bq m^{-2}.

The Health and Safety Laboratory (HASL) also provided estimates of globally produced ^{90}Sr deposition in the O-20 degree latitude band (HASL 1974). Figure 4, pg. I-35 of their report is similar to the estimates provided by UNSCEAR (1993). Their estimates of ^{90}Sr deposition were 10-20 mCi ^{90}Sr km^{-2}. Converting these estimates to comparable units of ^{137}Cs deposition and decay correcting to 1982 results in a range of ^{137}Cs deposition of 481 to 963 Bq m^{-2}. The median value of this range is 722 Bq m^{-2}.

Figure 6-1 compares these estimates of ^{137}Cs deposited in the Marshall Islands from global sources. The estimates from Simon, LBL and HASL compare well with this study's estimate. It has been noted in previous paragraphs that Musolino used soil sampling from Majuro as the "background estimate." It is not possible to rule out that Majuro may have been affected by fallout from the PPG testing, therefore, these estimates must be considered to be higher than that from global fallout alone and thus, this study's estimates are considered to be valid for use in this assessment.

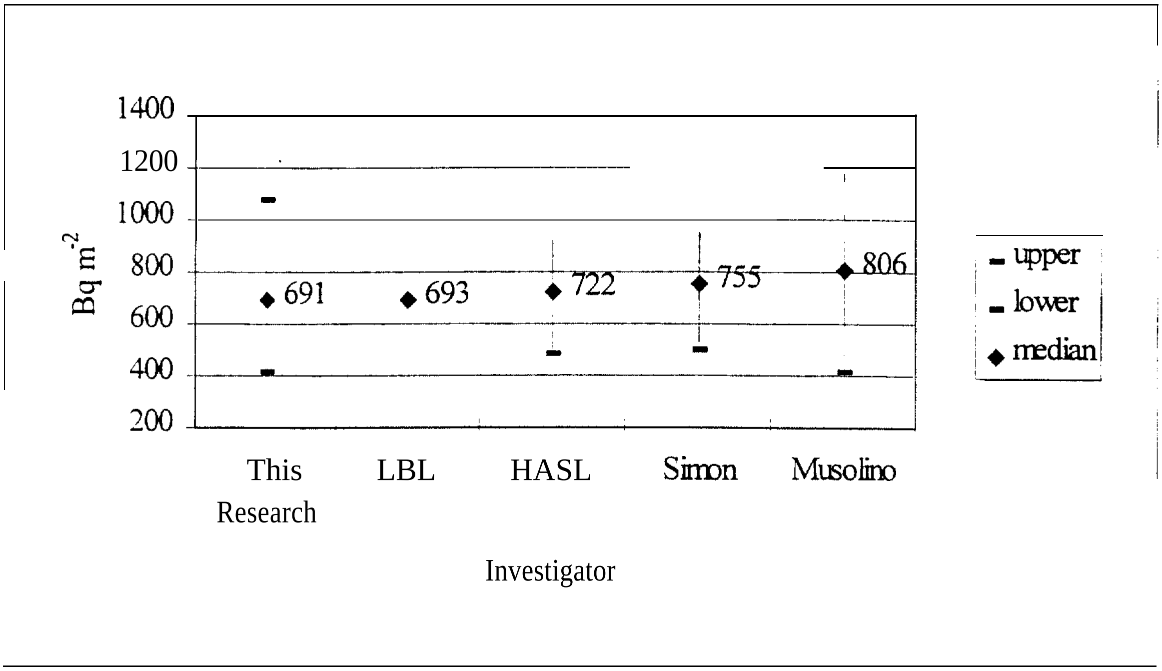

Figure 6- 1 Comparison of estimates of ^{137}Cs deposition from global sources.

Deposition to Soil Concentration Estimates

The deposition estimates provided in the previous chapter are converted to soil concentrations for use in the method validation. The equations described in the Methods Section including the Monte Carlo uncertainty calculations produced the following Table (6-l) of results.

A description of the deposition to soil concentration conversions is provided in the following paragraphs. These paragraphs describe, in deterministic fashion, the conversion implemented for each atoll.

Table 6-l Distribution Percentiles for Estimated Soil ^{137}Cs Concentration (Bq kg^{-1}) for Selected Atolls.

Atoll	Distribution Percentile				
	5th	25th	50th	75th	95th
Kwajalein	6.8	8.3	9.8	11.6	14.4
Maj uro	2.1	2.9	3.6	4.4	5.8
Rongelap	448.0	568.4	678.0	817.5	1084.9
Rongerik	390.1	506.1	608.2	729.9	975.3
Ujelang	3.9	4.9	5.6	6.5	8.1
Utirik	60.3	71.2	81.6	95.6	123.1
Wotho	7.3	8.5	9.6	11.0	13.4

Kwajalein. The total estimated deposition for Kwajalein was 2,8 13 Bq $^{137}Cs\ m^{-2}$. Because of radioactive decay, about 1,548 Bq $^{137}Cs\ m^{-2}$ remained in 1982. Only 72% of this deposited amount resides in the 0- 15 cm layer. Therefore. the estimated ^{137}Cs concentration in the O-15 cm layer of Kwajalein soil is 6.19 Bq kg^{-1}.

The next step in the process is to add in the amount of ^{137}Cs from global fallout residing in the O-l 5 cm soil profile layer. This addition is necessary for comparison to contemporary soil measurements. The median estimate of global ^{137}Cs fallout in the RMI is 69 1 Bq m^{-2}. If the entire deposit were contained in the O-l 5 cm layer. the soil concentration would be 4.16 Bq kg^{-1}. However, it has already been determined that approximately 72% of the ^{137}Cs resides in the O-15 cm soil profile layer. Therefore, the product of this percentage and the total soil concentration of 4.16 Bq kg' produces a concentration of 3.0 Bq kg^{-1} in the O-l 5 cm layer from global sources. Adding this value to the estimate of ^{137}Cs deposition from testing in the RMI produces a total estimated soil concentration of 9.19 Bq kg-‘.

Rongelap. The total estimated deposition for Rongelap was 279,773 Bq ^{137}Cs m^{-2}. Because of radioactive decay, about 147,560 Bq ^{137}Cs m^{-2} remained in 1982. Only 82% of this deposited amount resides in the O-l 5 cm layer. Therefore, the estimated ^{137}Cs concentration in the O-l 5 cm layer of Rongelap soil is 668 Bq kg-‘.

The next step in the process is to add in the amount of ^{137}Cs from global fallout residing in the O-l 5 cm soil profile layer. This addition is necessary for comparison to contemporary soil measurements. The median estimate of global ^{137}Cs fallout in the RMI is 69 l Bq m^{-2}. If the entire deposit were contained in the O-l 5 cm layer, the soil concentration would be 4.16 Bq kg-‘. However, it has already been determined that approximately 82% of the ^{137}Cs resides in the O-1 5 cm soil profile layer. Therefore, the product of this percentage and the total soil concentration of 4.16 Bq kg^{-1} produces a concentration of 3.4 Bq kg“ in the O-l 5 cm layer from global sources. Adding this value to the estimate of ^{137}Cs deposition from testing in the RMI produces a total of 671.7 Bq kg-‘.

Rongerik. The total estimated deposition for Rongerik was 25 1,805 Bq ^{137}Cs m^{-2}. Because of radioactive decay, about 132.343 Bq ^{137}Cs m^{-2} remained in 1982. Only 83% of this deposited amount resides in the O-l 5 cm layer. Therefore, the estimated ^{137}Cs concentration in the O-l 5 cm layer of Rongerik soil is 609 Bq kg“.

The next step in the process is to add in the amount of ^{137}Cs from global fallout residing in the O-15 cm soil profile layer. This addition is necessary for comparison to contemporary soil measurements. The median estimate of global ^{137}Cs fallout in the RMI is 691 Bq m^{-2}. If the entire deposit were contained in the O-15 cm layer, the soil concentration would be 4.16 Bq kg^{-1}. However, it has already been determined that approximately 83% of the ^{137}Cs resides in the O-15 cm soil profile layer. Therefore, the product of this percentage and the total soil concentration of 4.16 Bq kg^{-1} produces a concentration of 3.4 Bq kg^{-1} in the 0- 15 cm layer from global sources. Adding this value to the estimate of ^{137}Cs deposition from testing in the RMI produces a total estimated soil concentration of 6 12.2 Bq kg“.

Ujelang. The total estimated deposition for Ujelang was 1,282 Bq ^{137}Cs m^{-2}. Because of radioactive decay, about 695 Bq ^{137}Cs m^{-2} remained in 1982. Only 71% of this deposited amount resides in the O-15 cm layer. Therefore, the estimated ^{137}Cs concentration in the O-l 5 cm layer of Ujelang soil is 2.8 Bq kg^{-1}.

The next step in the process is to add in the amount of ^{137}Cs from global fallout residing in the O-l 5 cm soil profile layer. This addition is necessary for comparison to contemporary soil measurements. The median estimate of global ^{137}Cs fallout in the RMI is 691 Bq m^{-2}. If the entire deposit were contained in the O-15 cm layer, the soil concentration would be 4.16 Bq kg^{-1}. However, it has already been deterrnined that approximately 7 I % of the ^{137}Cs resides in the 0- 15 cm soil profile layer. Therefore, the product or‘ this percentage and the total soil concentration of 4.16 Bq kg-’ produces a concentration of 3.0 Bq kg“ in the 0- 15 cm layer from global sources. Adding this value to the estimate of ^{137}Cs deposition from testing in the RMI produces a total estimated soil concentration of 5.7 Bq kg-‘.

Utirik. The total estimated deposition for Utirik was 29,736 Bq ^{137}Cs m^{-2}. Because of radioactive decay, about 15,643 Bq ^{137}Cs m^{-2} remained in 1982. Only 85% of this deposited amount resides in the O-l 5 cm layer. Therefore, the estimated ^{137}Cs concentration in the O-l 5 cm layer of Utirik soil is 73.6 Bq kg“.

The next step in the process is to add in the amount of ^{137}Cs from global fallout residing in the O-l 5 cm soil profile layer. This addition is necessary for comparison to contemporary soil measurements. The median estimate of global ^{137}Cs fallout in the RMI is 691 Bq m^{-2}. If the entire deposit were contained in the O-l 5 cm layer, the soil concentration would be 4.16 Bq kg^{-1}. However, it has already been determined that approximately 85% of the ^{137}Cs resides in the O-l 5 cm soil profile layer. Therefore, the product of this percentage and the total soil concentration of 4.16 Bq kg^{-1} produces a concentration of 3.5 Bq kg^{-1} in the 0- 15 cm layer from global sources. Adding this value to the estimate of ^{137}Cs deposition from testing in the RMI produces a total estimated soil concentration of 77.2 Bq kg^{-1}.

Wotho. The total estimated deposition for Wotho was 2,18 1 Bq ^{137}Cs m^{-2}. Because of radioactive decay, about 1,187 Bq ^{137}Cs m^{-2} remained in 1982. Only 86% of this deposited amount resides in the O-l 5 cm layer. Therefore, the estimated ^{137}Cs concentration in the O-l 5 cm layer of Wotho soil is 5.7 Bq kg^{-1}.

The next step in the process is to add in the amount of ^{137}Cs from global fallout residing in the O-l 5 cm soil profile layer. This addition is necessary for comparison to contemporary soil measurements. The median estimate of global ^{137}Cs fallout in the RMI is 691 Bq m^{-2}. If the entire deposit were contained in the O-l 5 cm layer, the soil concentration would be 4.16 Bq kg-‘. However, it has already been determined that approximately 86% of the ^{137}Cs resides in the O-l 5 cm soil profile layer. Therefore, the product of this percentage and the total soil concentration of 4.16 Bq kg^{-1} produces a concentration of 3.6 Bq kg^{-1} in the 0-15 cm layer from global sources. Adding this value to the estimate of ^{137}Cs deposition from testing in the RMI produces a total estimated soil concentration of 9.3 Bq kg^{-1}.

Validation

The validation step compares the estimates of soil concentrations with contemporary measurements from the Nationwide Radiological Survey. This comparison was also performed using Monte Carlo simulations. These uncertainty analyses produced a lognormal distribution of P/O's. An example distribution is displayed in Figure 6-2.

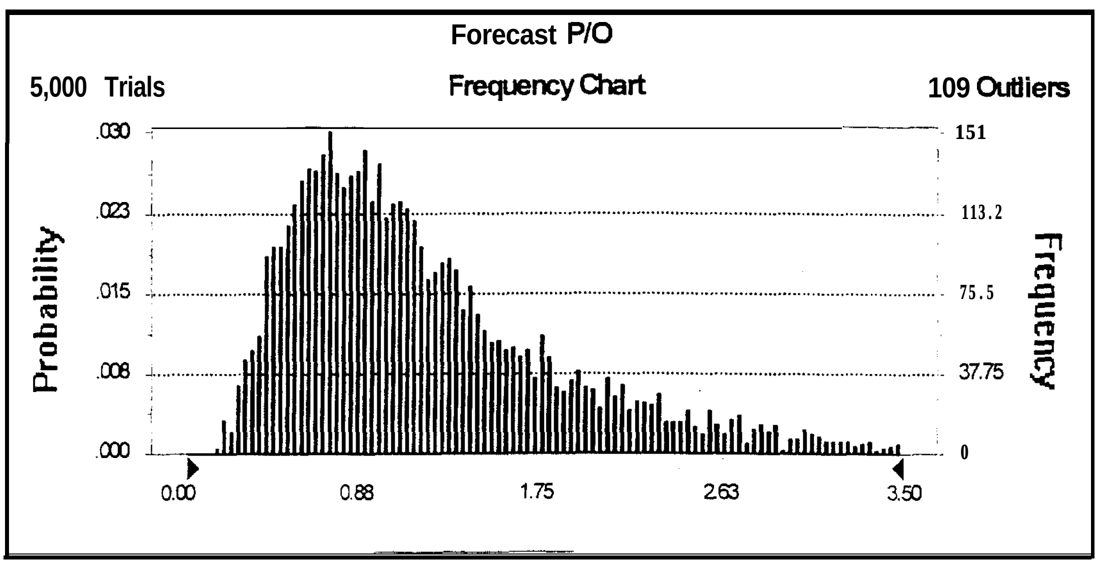

Figure 6-2 Example Distribution of P/O ratios Generated by Monte Carlo Analysis.

The distributions of P/O ratios for each atoll are displayed in Figure 6-3. The median P/O estimates for each atoll are close to unity indicating good agreement between predictions and observations. An exception to this statement is Ujelang. The majority of P/O estimates for this atoll are less than one. This indicates that this project is under-predicting ^{137}Cs concentrations for this atoll.

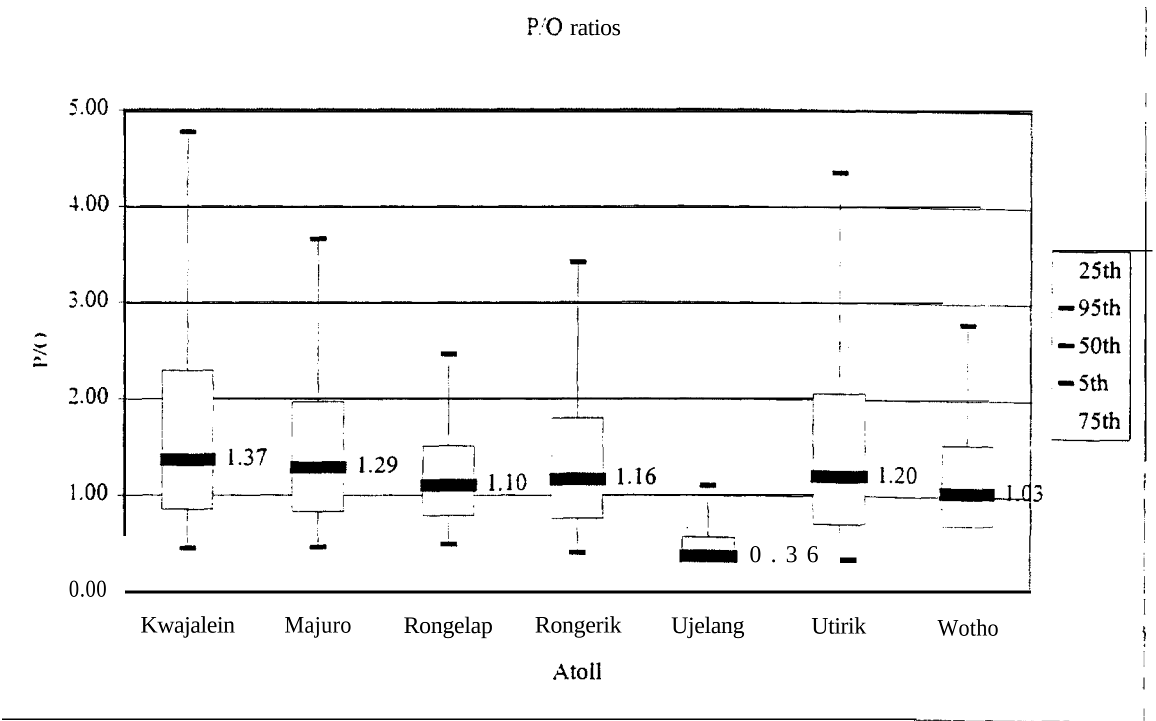

Figure 6-3 Comparison of Distributed P/O Ratios for Each Atoll.

A table of these percentile distributions is given below. Also included in this table is the geometric bias calculation for each percentile. Results indicate that the deposition estimate methods using both historical exposure rate and gummed film measurements are quite good.

Table 6-2 Summary of Validation Results.

Atoll	Percentile Distributions				
	5th	25th	50th	75th	95th
Kwajalein	0.44	0.85	1.37	2.29	4.77
Majuro	0.45	0.83	1.29	1.97	3.66
Rongelap	0.48	0.79	1.10	1.51	2.46
Rongerik	0.39	0.76	1.16	1.80	3.42
Ujelang	0.12	0.23	0.36	0.56	1.10
Utirik	0.33	0.70	1.20	2.06	4.36
Wotho	0.40	0.70	1.03	1.54	2.79
Geometric Bias	0.35	0.65	1.00	1.55	2.95

The overall geometric bias of 1 .O shows quite good agreement between predictions and observations. However, the geometric bias for predictions based only on gummed film or exposure rate measurements shows a slight over-prediction. For example, calculations based on gummed film measurements for Kwajalein and Majuro give a median geometric bias of 1.33. Calculations based on exposure rate measurements for Rongelap, Rongerik, Utirik, and Wotho (excluding Ujelang) give a median geometric bias of 1.12. Geometric bias for these individual calculations is given in Table 6-3.

Table 6-3 Geometric Bias for Predictions based on either Gummed Film or Exposure Rate Data.

Historical Data	Percentile Distributions				
	5th	25”	50”	75’”	95”
Gummed Film	0.45	0.84	1.33	2.13	4.18
Exposure Rate [a]	0.40	0.74	1.12	1.71	3.18

[a] Excludes data from Ujelang

CHAPTER 7
RESULTS AND CONCLUSIONS

Introduction

This final chapter discusses the results of the model's predictions for estimating the deposition of ^{137}Cs in the Marshall Islands. The predictive capabilities of each method using exposure rate and gummed film measurements are discussed. Recommendations and conclusions based on these outputs are also provided. Finally, this chapter presents recommendations concerning the use of these methods in future work.

Deposition Results

Global Fallout Estimate Results

Global fallout estimates in the RMI have been made using UNSCEAR methods and relative annual ^{137}Cs deposition rates from Denmark. The estimated median ^{137}Cs deposition in 1982 for the Marshall Islands was 691 Bq m^{-2} with 5^{th} and 95^{th} percentiles of 492 and 925 Bq m^{-2} respectively. The minimum and maximum values for the uncertainty range nere 4 1 7 and 1076 Bq m^{-2} respectively, with an arithmetic average of 697 Bq m^{-2}. These results were compared to estimates made by other researchers and found to be in good agreement (difference between median estimates <10%). The slightly lower median estimate from this study is primarily due to subtracting the portion of global fallout originating in the RMI from the annual global depositions occurring during 1946 through 1958. The uncertainty distribution of the estimates encompassed the range of estimates made by others. As a result of this comparison, it is concluded that global fallout estimates of this study are valid for the RMI.

Deposition Estimate Results

Cesium- 137 deposition estimates for several RMI Atolls were made using Hicks methods and historical gummed film and exposure rate data. Table 7-l summarizes the deposition estimates for these atolls. The Castle Series tests were responsible for the

Table 7-l Summary of ^{137}Cs Deposition (Bq m^{-2}) Results using Gummed Film and Exposure Rate Measurements.

Atoll	Series[a]			
	Ivy	Castle	Redwing	Hardtack I
Kwajalein	7.3 (5.1-9.5)	489.5 (443.2-540.3)	890.7 (778.7-1,005.0)	216.7 (187.0-256.4)
Maj uro	3.4 (2.1-4.7)	180.5 (152.3-220.2)		
Rongelap	0.0	146685.4 (123,835.1-169,408.4)	59.5 (49.6-69.2)	233.2 (210.9-256.9)
Rongerik	3.8 (3.1-4.4)	132282.4 (112,844.0-152,216.3)	113.0 (102.1-124.7)	
Ujelang	0.0	330.2 (298.6-360.3)	196.6 (172.6-221.5)	105.5 (96.3-l 14.5)
Utirik	15.1 (8.9-21.3)	15448.8 (13,902.9-16,960.2)	65.3 (59.1-71.6)	155.1 (138.7-172.3)
Wotho	7.5 (4.4-10.6)	496.4 (392.0-606.1)	431.8 (366.0-500.5)	250.5 (215.7-285.6)

[a] Values in parentheses are the 5th and 95'" percentile range for each Series.

majority of fallout on many of the atolls. However, Kwajalein received more deposition from Redwing than that from Castle or Hardtack I. Wotho's combined deposition from Redwing and Hardtack I was greater than the amount from Castle. Evidence like this suggests that although the Castle Series was a major contributor to fallout at many of the RMI atolls, it was not the major contributor at all atolls.

Validation Results

Comparisons of cumulative deposition estimates with contemporary soil concentrations were made as part of the methods validation. Table 7-2 summarizes these validation results. There is divergence between predicted and observed concentrations

Table 7-2 Summary of Validation Results.

Atoll	Input Data	Median (P/O)	Uncertainty range in (P/O)[a]
Kwajalein	Gummed Film	1.37	0.4 - 4.8
Majuro	Gummed Film	1.29	0.5 - 3.7
Rongelap	Exposure Rate	1.10	0.5 - 2.5
Rongerik	Exposure Rate	1.16	0.4 - 3.4
Ujelang	Exposure Rate	0.36	0.1 - 1.1
Utirik	Exposure Rate	1.20	0.3 - 4.4
Wotho	Exposure Rate	1.03	0.4 - 2.8
Geometric Bias (All Data)		1.0	0.3 – 2.9
Geometric Bias (Gummed Film Only)		1.33	0.4 – 4.2
Geometric Bias (Exposure Rate Only w/o Ujelang)		1.12	0.4 – 3.2

[a] Uncertainty range = 5th and 95"' percentiles.

for particular locations and for different media. For example, the bias in predictions based on Gummed Film measurements is slightly higher than the bias in predictions based on exposure rate measurements. This over-prediction for the heavily urbanized atolls of Kwajalein and Majuro could be a result of soil disturbance by human activity thereby making it difficult to obtain a representative sample. These slight over-predictions using both Gummed Film and exposure rate measurements could also be due to minor losses due to weathering and biological removal not accounted for in the deposition estimates of this project.

Under-predictions in ^{137}Cs deposition were obtained for Ujelang. A review of the exposure rate data seems to indicate rhat other tests may have contributed to the deposition. For esample, Ivy King (500 kton) produced larger exposure rate readings than Ivy Mike. Also, Ujelang is closer to Enewetak than it is to Bikini Atoll. This close proximity may have resulted in depositions from lower yield tests (e.g., < 1 Mton) conducted on Enewetak. Therefore, it is reasonable to assume that these under-predictions may be the result of depositions occurring from other tests not accounted for in this assessment.

When viewed in the aggregate, the agreement between predicted and observed concentrations in the Marshall Islands' environment is excellent (overall Geometric bias = 1 .O). This provides confidence that the methods used in this study are reasonable and reliable.

Sensitivity Analysis Results

The sensitivity analysis was performed during the uncertainty analysis with Crystal Ball. Crystal Ball calculated sensitivity by computing rank correlation coefficients behveen each assumption and forecast cell while running the simulation. The results of this sensitivity analysis are provided in Figure 7-l.

Soil fraction (percent of ^{137}Cs residing in the O-15 cm soil profile layer) had a positive influence on the estimated soil concentrations at each atoll. The influences were greatest for Kwajalein and Majuro and to lesser degrees at the remaining atolls.

Estimated global soil concentrations also had a positive influence on the estimated soil concentrations at each atoll. These influences were least at Rongelap, Rongerik, and Utirik where the cumulative depositions and soil concentrations were greatest. This is an obvious result in view of adding the large deposition at these atolls to the small contribution from global fallout. The opposite effect is apparent at the remaining atolls where estimated depositions and cumulative soil concentrations were smaller.

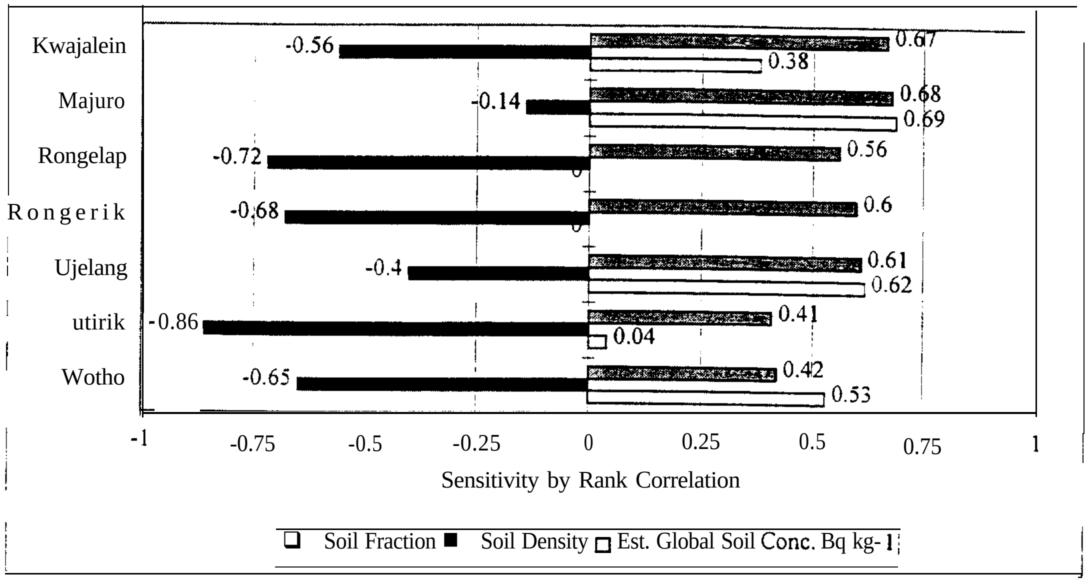

Figure 7-l Sensitivity Analysis by Rank Correlation for all Atolls.

Soil density had a negative influence on estimated soil concentrations at each atoll. This parameter was a divisor in the calculation and thus would exhibit this negative influence. The greatest negative influences were observed at Rongelap, Rongerik, and Utirik. Results were less sensitive to these effects at the remaining atolls.

Individual exposure rate measurements and Gummed Film measurements all produced much less influence on predictions. The sensitivities for these individual measurements were all significantly less than the smallest sensitivities shown in Figure 7- 1.

Conclusions Based on Deposition Estimates

The primary purpose of this study was to develop and test computerized methods to estimate the deposition of ^{137}Cs in the Marshall Islands. This work is now complete. Based on the results this research work. several conclusions can be made.

The first conclusion is that the methods produce reasonable estimates of deposition. A review of the geometric bias reveals that the 25th and 75th percentile predictions (with the exception of Ujelang) are within a factor of two of observations (e.g., geometric bias of 0.5 to 2). This provides confidence that the methods are reliable. Following this first conclusion. another logical conclusion is that the methods work with the input of historical exposure rate and gummed film measurements.

The next conclusion is that the global fallout deposition estimates are valid. One part of this conclusion is based on the comparison with estimates of other researchers. The other part of this conclusion is based on the fact that the predictions are a summation of deposition estimates and global fallout estimates. If the global fallout estimates were significantly flawed, the total depositions would be erroneous and the resulting geometric bias would be much greater.

The final conclusion is that ^{137}Cs deposition occurred on many atolls more distant than Rongelap, Rongerik and Utirik Atolls. Results of this reconstruction work give evidence that radioactive fallout occurred at atolls further south of the four northern atolls recognized by DOE as being affected by fallout. In addition, this cumulative ^{137}Cs deposition is higher (1.2, 2,2.2.5 2.5.5. 16 and 2 10 times higher at Majuro, Kwajalein, Wotho, Ujelang, Utirik, and Rongelap respectively) (Takahashi et al. 1997) than that from global fallout alone. This is especially true considering that the greatest fallout from global sources occurred during the early 1960's (refer to Figure 5-1, page 72). This period occurred after testing in the PPG ceased in 1958. CDC should analyze the statistical significance of the elevated ^{137}Cs depositions as discussed in the recommendations that follow.

<u>Recommendations</u>

One of the troubling problems facing any dose reconstruction effort is missing data. This deposition reconstruction effort also experienced this problem with missing data. Therefore, the primary recommendation stemming from this research is to continue to search for additional information.

Another recommendation is to compare contemporary soil concentrations on all atolls with the validated global fallout estimates from this research. This comparison could be useful to determine which atolls have statistically significant elevated levels of ^{137}Cs in soil above the global fallout estimates. CDC can use the results of this comparison to prioritize future work.

Now that these methods have been tested with ^{137}Cs, future work should be done to estimate iodine deposition. These iodine deposition estimates could then be compared to ^{131}I measurements in air during Operation Hardtack I on Rongelap, Ujelang, Utirik, and Wotho Atoll (PHS 1958). Once these ^{131}I deposition estimates are reconstructed and validated, the results can be used to calculated potential iodine exposures to populations at offsite atolls.

Future work to reconstruct ^{131}I deposition should consider the use of contemporary soil ^{137}Cs concentrations, contemporary measurements of ^{129}I in archival soil samples, and fallout TOA to reconstruct iodine at other atolls. This work would benefit reconstruction on atolls where there is limited or no measurement information.

GLOSSARY

Term	Description
AS	Aerial Survey
AEC	Atomic Energy Commission, predecessor of the Department of Energy (DOE)
AWS	Air Weather Service of the U.S. Air Force
Bq	Becquerel. activity, one disintegration per second (dps)
BNL	Brookhaven National Laboratory
CDC	Centers for Disease Control and Prevention
Ci	Curies. 1 Ci = 3.7E10 dps
CIC	Coordination and Information Center
DF	Decay Factor
DOE	Department of Energy
EML	Environmental Measurements Laboratory
FM	Fixed Monitor
Fractionation	The ratio of Refractory to Volatile elements in the fallout material. A fractionation value of 0.5 indicates that only 1/2 of the refractory elements are present relative to volatile elements.
GCT	Greenwich Civil Time - a global time reference used by the military to address all times to a common time. The Marshall Islands local time is GCT + 1/2 day.
GF	Gummed Film
GM	Gieger Mueller
GS	Ground Survey
HASL	Health and Safety Laboratory (predecessor of the EML)
HPGe	High Purity Germanium
IC	Ionization Chamber
JTF	Joint Task Force
kCi	Kilo Curie, one thousand Curies (Ci)
kton	Kilo ton. or thousand tons of TNT equivalent explosive energy
LBL	Lawrence Berkeley Laboratory
LLNL	Lawrence Livermore National Laboratory
MCi	Mega Curie. or million Curies of activity, 1 Ci = 3.7E10 Bq or dps
Mton	Mega ton. or million tons of TNT equivalent explosive energy
MDA	Minimum Detectable Activity
MOHE	Ministry of Health and Environment
NAS	National Academy of Sciences
NCEH	National Center for Environmental Health

Term	Description
NCI	National Cancer Institute
ND	Normalized Deposition Factor
NRDL	Naval Radiological Defense Laboratory
NTS	Nevada Test Site
NWRS	Nationwide Radiological Survey
NYO	New York Operations Office
ORERP	Offsite Radiation Exposure Review Project
PBq	Penta Becquerels, 1 PBq = 1 El 5 Bq or 1E 15 dps
PHS	Public Health Service
PPG	Pacific Proving Ground
RMI	Republic of the Marshall Islands
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
USWB	U.S. Weather Bureau
UWAFL	University of Washington Applied Fisheries Laboratory
WHO	World Health Organization

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APPENDIX

Table A-l. Aerial Survey Data from Operation Castle.

Flight Pattern	Atoll	Island	Local Date	Local Time	mR hr^{-1}
Able	Ailinginae	Ailinginae	3/2/54	1:28 PM	400
Able	Ailinginae	Sifo	3/4/54	10:04 AM	240
Able	Ailinginae	Mogiri	3/4/54	10:05 AM	280
Able	Ailinginae	Knox	3/4/54	10:11 AM	390
Able	Ailinginae	Charaien	3/4/54	10:14 AM	200
Able	Ailinginae	Ailinginae	3/4/54	1:35 PM	330
Able	Ailinginae	Sifo	3/19/54	5:10 PM	20
Able	Ailinginae	Mogiri	3/19/54	5:11 PM	20
Able	Ailinginae	Un-named	3/19/54	5:12 PM	24
Able	Ailinginae	Un-named	3/19/54	5:14 PM	32
Able	Ailinginae	Ucchuwanen	3/19/54	5:16 PM	40
Able	Ailinginae	Knox	3/19/54	5:18 PM	80
Able	Ailinginae	Enibuk	3/28/54	11:23 AM	6
Able	Ailinginae	Enibuk	3/31/54	10:05 AM	26
Able	Ailinginae	Enibuk	4/8/54	10:22 AM	57
Able	Ailinginae	Enibuk	4/12/54	10:59 AM	7.7
Able	Ailinginae	Enibuk	4/21/54	9:52 AM	2.4
Able	Ailinginae	Enibuk	4/27/54	10:29 AM	1.6
Able	Ailinginae	Enibuk	5/1/54	8:30 AM	0.04
Able	Ailinginae	Enibuk	5/6/54	10:24 AM	0.8
Able	Ailinginae	Enibuk	5/7/54	10:05 AM	10
Able	Ailinginae	Enibuk	5/8/54	9:16 AM	1.2
Able	Ailinginae	Enibuk	5/15/54	8:54 AM	1.4
Able	Ailinginae	Enibuk	5/16/54	8:23 AM	0.8
Baker	Ailinglaplap	Ailinglaplap	3/3/54	7:45 AM	0.08
Baker	Ailinglaplap	Ailinglaplap	4/3/54	8:57 AM	0.6
Baker	Ailinglaplap	Ailinglaplap	4/12/54	9:37 AM	0.4
Baker	Ailinglaplap	Ailinglaplap	4/21/54	11:31 AM	0
Baker	Ailinglaplap	Ailinglaplap	5/2/54	10:13 AM	0.04
Baker	Ailinglaplap	Ailinglaplap	5/9/54	9:43 AM	0
Baker	Ailinglaplap	Ailinglaplap	5/16/54	6:55 AM	0
Able	Ailuk	Ailuk	3/2/54	5:16 PM	76
Able	Ailuk	Ailuk	3/4/54	6:10 PM	20
Able	Ailuk	Kapen	3/19/54	7:38 PM	
Able	Ailuk	Un-named	3/19/54	7:39 PM	2

Table A-1 - - continued.

Flight Pattern	Atoll	Island	Local Date	Local Time	mR hr^{-1}
Able	Ailuk	Un-named	3/19/54	7:40 PM	1.6
Able	Ailuk	Un-named	3/19/54	7:41 PM	2
Able	Ailuk	Ailuk	3/19/54	7:42 PM	1
Able	Ailuk	Kapen	3/28/54	2:53 PM	1.6
Able	Ailuk	Kapen	3/31/54	1:45 PM	2.4
Able	Ailuk	Kapen	4/8/54	1:58 PM	1.7
Able	Ailuk	Kapen	4/12/54	2:41 PM	0.8
Able	Ailuk	Kapen	4/21/54	1:23 PM	0.1
Able	Ailuk	Kapen	4/27/54	2:02 PM	0.4
Able	Ailuk	Kapen	5/1/54	11:59 AM	0.6
Able	Ailuk	Kapen	5/6/54	2:00 PM	0.2
Able	Ailuk	Kapen	5/7/54	1:30 PM	7.6
Able	Ailuk	Kapen	5/8/54	12:45 PM	0.7
Able	Ailuk	Kapen	5/15/54	12:28 PM	0.4
Able	Ailuk	Kapen	5/16/54	11:43 AM	0.1
Baker	Arno	Arno	3/3/54	10:28 AM	0.6
Baker	Amo	Arno	4/3/54	11:46 AM	0.9
Baker	Arno	Amo	4/12/54	12:25 PM	1.2
Baker	Amo	Amo	4/21/54	2:34 PM	0.4
Baker	Arno	Amo	5/2/54	1:07 PM	0.04
Baker	Amo	Arno	5/9/54	12:31 PM	0.2
Baker	Arno	Amo	5/16/54	10:00 AM	0.02
Baker	Aur	Aur	3/3/54	9:45 AM	0.4
Baker	Aur	Ani	4/3/54	12:19 PM	0.9
Baker	Aur	Ani	4/12/54	1:09 PM	0.2
Baker	Aur	Ani	4/21/54	3:08 PM	0
Baker	Aur	Ani	5/2/54	1:38 PM	0.04
Baker	Aur	Ani	5/9/54	1:05 PM	0.3
Baker	Aur	Ani	5/16/54	10:30 AM	0.04
Able	Bikar	Bikar	3/2/54	4:28 PM	600
Able	Bikar	Bikar	¾/54	4:32 PM	160
Able	Bikar	Jaboerukku	3/19/54	6:48 PM	28
Able	Bikar	Bikar	3/19/54	6:49 PM	28
Able	Bikar	Bikar	3/28/54	2:14 PM	0.08
Able	Bikar	Bikar	3/31/54	12:57 PM	15
Able	Bikar	Bikar	4/8/54	1:12 PM	20
Able	Bikar	Bikar	4/12/54	1:45 PM	8
Able	Bikar	Bikar	4/21/54	12:41 PM	0.4
Able	Bikar	Bikar	4/27/54	11:18 Phl	0
Able	Bikar	Bikar	5/1/54	11:11 AM	3.7
Able	Bikar	Bikar	5/6/54	1:15 PM	15
Able	Bikar	Bikar	5/7/54	12:47 PM	34

Table A-l - - continued.

Flight Pattern	Atoll	Island	Local Date	Local Time	mR hr^{-1}
Able	Bikar	Bikar	5/8/54	12:03 PM	4
Able	Bikar	Bikar	5/15/54	11:42 AM	3
Able	Bikar	Bikar	5/16/54	11:03 AM	1.7
Able	Bikini	Enyu	¾/54	9:00 AM	1200
Able	Bikini	Namu	¾/54	9:13 AM	96000
Able	Bikini	Sse Namu	¾/54	9:24 AM	80
Able	Bikini	Enirik	¾/54	9:27 AM	120
Able	Bikini	Air Strip	¾/54	9:28 AM	240
Able	Bikini	Bikini	¾/54	9:36 AM	5800
Able	Bikini	Bikini	3/31/54	9:39 AM	110
Able	Bikini	Bikini	4/12/54	10:36 AM	8.7
Able	Bikini	Bikini	4/21/54	9:32 AM	52
Able	Bikini	Bikini	4/27/54	10:08 AM	720
Able	Bikini	Bikini	5/1/54	8:10 AM	960
Able	Bikini	Bikini	5/6/54	10:02 AM	25600
Able	Bikini	Bikini	5/7/54	9:48 AM	22400
Able	Bikini	Bikini	5/8/54	8:52 AM	3190
Able	Bikini	Bikini	5/15/54	8:33 AM	920
Able	Bikini	Bikini	5/16/54	7:56 AM	1060
Baker	Ebon	Ebon	3/3/54	12:47 PM	0.2
Baker	Ebon	Ebon	4/3/54	9:59 AM	1.1
Baker	Ebon	Ebon	4/12/54	10:37 AM	0.2
Baker	Ebon	E b o n	4/21/54	12:34 PM	0.1
Baker	Ebon	Ebon	5/2/54	11:14 AM	0.04
Baker	Ebon	Ebon	5/9/54	10:43 AM	0.2
Baker	Ebon	Ebon	5/16/54	8:09 AM	0
Baker	Erikub	Erikub	3/3/54	9:02 AM	4
Baker	Erikub	Bogengoa	4/3/54	12:53 PM	0.9
Baker	Erikub	Bogengoa	4/12/54	1:52 PM	0.2
Baker	Erikub	Bogengoa	4/21/54	3:47 PM	0.4
Baker	Erikub	Bogengoa	5/2/54	2:32 PM	0
Baker	Erikub	Bogengoa	5/9/54	1:22 PM	0
Baker	Erikub	Bogengoa	5/16/54	11:05 AM	0.1
Baker	Jaluit	Jaluit	3/3/54	12:06 PM	0.2
Baker	Jaluit	Jaluit	4/3/54	10:35 AM	1.4
Baker	Jaluit	Jaluit	4/12/54	11:16 AM	0.3
Baker	Jaluit	Jaluit	4/21/54	1:10 PM	0.04
Baker	Jaluit	Jaluit	5/2/54	11:52 AM	0.04
Baker	Jaluit	Jaluit	5/9/54	11:20 AM	0
Baker	Jaluit	Jaluit	5/16/54	8:45 AM	0.04
Able	Jemo	Jemo	3/2/54	5:28 PM	18
Able	Jemo	Jemo	3/4/54	6:20 PM	12

Table A-l - - continued.

Flight Pattern	Atoll	Island	Local Date	Local Time	mR hr-1
Able	Jemo	Jemo	3/19/54	7:51 PM	0.02
Able	Jemo	Jemo	3/28/54	3:08 PM	0.8
Able	Jemo	Jemo	3/31/54	2:00 PM	2.4
Able	Jemo	Jemo	4/8/54	2:07 PM	2
Able	Jemo	Jemo	4/12/54	2:50 PM	0.4
Able	Jemo	Jemo	4/21/54	1:32 PM	0.08
Able	Jemo	Jemo	4/27/54	2:10 PM	0
Able	Jemo	Jemo	5/1/54	12:09 PM	0.1
Able	Jemo	Jemo	5/6/54	2:10 PM	0.2
Able	Jemo	Jemo	5/7/54	1:39 PM	3.2
Able	Jemo	Jemo	5/8/54	12:54 PM	0.3
Able	Jemo	Jemo	5/15/54	12:48 PM	0.4
Able	Jemo	Jemo	5/16/54	11:57 AM	0.2
Baker	Kili	Kili	3/3/54	12:24 PM	0.2
Baker	Kili	Kili	4/3/54	10:04 AM	0.9
Baker	Kili	Kili	4/12/54	11:04 AM	0.3
Baker	Kili	Kili	4/21/54	1:00 PM	0.09
Baker	Kili	Kili	5/2/54	11:41 AM	0
Baker	Kili	Kili	5/9/54	11:09 AM	0
Baker	Kili	Kili	5/16/54	8:35 AM	0.02
Charlie	Kusaie	Un-named	3/3/54	1:01 PM	0.8
Charlie	Kusaie	Un-named	5/2/54	11:12 AM	0.01
Charlie	Kusaie	Un-named	5/9/54	10:38 AM	0.04
Charlie	Kusaie	Un-named	5/16/54	9:34 AM	0.08
Charlie	Ku-ajalein	Un-named	3/3/54	11:35 AM	0.6
Charlie	Kwaj alein	Un-named	3/3/54	12:05 PM	0.2
Charlie	Kn-aj alein	Un-named	3/3/54	1:10 PM	0.4
Able	Kwajalein	Kwaj alein	3/28/54	7:04 AM	0
Able	Kwajalein	Kwaj alein	3/31/54	2:35 PM	0.2
Baker	Kwajalein	Kwajalein	4/3/54	1:54 PM	1.4
Able	Kuaj alein	Kwajalein	4/8/54	2:54 PM	0.5
Baker	Kuaj alein	Kwaj alein	4/12/54	2:52 PM	0.4
Able	Kwajalein	Kwajalein	4/21/54	2:35 PM	0
Baker	Kwajalein	Kwaj alein	4/21/54	4:40 PM	0.3
Able	Ku-aj alein	Kwajalein	4/27/54	3:10 PM	0
Baker	Kwajalein	Kwaj alein	5/2/54	3:16 PM	0
Able	Kwajalein	Kwajalein	5/6/54	2:55 PM	0.4
Able	Kwajalein	Kwajalein	5/8/54	1:35 PM	0.2
Able	Kwajalein	Kwaj alein	5/15/54	1:35 PM	0.1
Able	Kwajalein	Kwajalein	5/16/54	12:36 PM	0.08
Able	Lae	Lae	3/2/54	12:10 PM	0.08
Able	Lae	Lae	3/4/54	7:10 AM	0.04

Table A-l - - continued.

Flight Pattern	Atoll	Island	Local Date	Local Time	mR hr^{-1}
Able	Lae	Lae	3/19/54	4:02 PM	0.01
Able	Lae	Lae	3/28/54	7:47 AM	0
Able	Lae	Lae	3/31/54	8:32 AM	0.08
Able	Lae	Lae	4/8/54	9:15 AM	0.2
Able	Lae	Lae	4/12/54	9:20 AM	0.04
Able	Lae	Lae	4/21/54	8:24 AM	0.3
Able	Lae	Lae	4/27/54	8:53 AM	0
Able	Lae	Lae	5/1/54	6:55 AM	0.04
Able	Lae	Lae	5/6/54	8:30 AM	0
Able	Lae	Lae	5/7/54	8:22 AM	1.2
Able	Lae	Lae	5/8/54	7:26 AM	0.1
Able	Lae	Lae	5/15/54	7:22 AM	0.2
Able	Lae	Lae	5/16/54	6:47 AM	0.08
Able	Likiep	Likiep	3/2/54	5:40 PM	6
Able	Likiep	Likiep	¾/54	6:30 PM	10
Able	Likiep	Likiep	3/19/54	8:08 PM	0.2
Able	Likiep	Likiep	3/28/54	3:17 PM	0.4
Able	Likiep	Likiep	3/31/54	2:07 PM	1
Able	Likiep	Likiep	4/8/54	2:14 PM	1.2
Able	Likiep	Likiep	4/12/54	2:57 PM	0.04
Able	Likiep	Likiep	4/21/54	1:43 PM	0.04
Able	Likiep	Likiep	4/27/54	2:22 PM	0.6
Able	Likiep	Likiep	5/1/54	12:16 PM	0.08
Able	Likiep	Likiep	5/6/54	2:15 PM	0.2
Able	Likiep	Likiep	5/7/54	1:46 PM	3.2
Able	Likiep	Likiep	5/8/54	1:02 PM	0.5
Able	Likiep	Likiep	5/15/54	12:56 PM	0.3
Able	Likiep	Likiep	5/16/54	12:02 PM	0.1
Baker	Majuro	Majuro	3/3/54	10:16 AM	2
Baker	Majuro	Majuro	4/3/54	11:53 AM	0.9
Baker	Majuro	Majuro	4/12/54	12:45 PM	0.2
Baker	Majuro	Majuro	4/21/54	2:45 PM	0.3
Baker	Majuro	Majuro	5/2/54	1:17 PM	0.1
Baker	Majuro	Majuro	5/9/54	12:36 PM	0
Baker	Majuro	Majuro	5/16/54	10:10 AM	0.02
Baker	Maleolap	Maleolap	3/3/54	9:24 AM	3.6
Baker	Maleolap	Taroa	4/3/54	12:30 PM	0.5
Baker	Maleolap	Taroa	4/12/54	1:28 PM	0.2
Baker	Maleolap	Taroa	4/21/54	3:22 PM	0.2
Baker	Maleolap	Taroa	5/2/54	1:49 PM	0
Baker	Maleolap	Taroa	5/9/54	1:14 PM	0.2
Baker	Maleolap	Taroa	5/16/54	10:45 AM	0.06

Table A-l - - continued.

Flight Pattern	Atoll	Island	Local Date	Local Time	mR hr^{-1}
Able	Mej it	Mejit	¾/54	5:35 PM	12
Baker	Mili	Mili	3/3/54	11:09 AM	0.6
Baker	Mili	Mili	4/3/54	11:25 AM	0.7
Baker	Mili	Mili	4/12/54	12:01 PM	0.8
Baker	Mili	Mili	4/21/54	2:01 PM	0.02
Baker	Mili	Mili	5/2/54	12:45 PM	0.1
Baker	Mili	Mili	5/9/54	12:11 PM	0
Baker	Mili	Mili	5/16/54	9:35 AM	0.02
Charlie	Mokil	Un-named	3/3/54	11:30 AM	0.6
Charlie	Mokil	Un-named	5/2/54	12:36 PM	0.02
Charlie	Mokil	Un-named	5/9/54	12:00 PM	0
Charlie	Mokil	Un-named	5/16/54	10:46 AM	0.04
Baker	Namorik	Namorik	3/3/54	2:23 PM	0.2
Baker	Namorik	Namorik	4/3/54	9:33 AM	0.7
Baker	Namorik	Namorik	4/12/54	10:13 AM	0.3
Baker	Namorik	Namorik	4/21/54	12:10 PM	0.2
Baker	Namorik	Namorik	5/2/54	10:50 AM	0.01
Baker	Namorik	Namorik	5/9/54	10:19 AM	0
Baker	Namorik	Namorik	5/16/54	7:36 AM	0
Baker	Namu	Namu	3/3/54	7:20 AM	0.02
Baker	Namu	Kaginen	4/3/54	8:34 AM	0.4
Baker	Namu	Kaginen	4/12/54	9:16 AM	0.4
Baker	Namu	Kaginen	4/21/54	11:12 AM	0.4
Baker	Namu	Kaginen	5/2/54	9:48 AM	0
Baker	Namu	Kaginen	5/9/54	9:22 AM	0.2
Baker	Namu	Kaginen	5/16/54	6:32 AM	0
Charlie	Pingelap	Un-named	3/3/54	1:04 PM	0.6
Charlie	Pingelap	Un-named	5/2/54	12:12 PM	0.05
Charlie	Pingelap	Un-named	5/9/54	11:35 AM	0.2
Charlie	Ponape	Un-named	3/3/54	9:45 AM	0.8
Charlie	Ponape	Un-named	5/2/54	1:09 PM	0.07
Charlie	Ponape	Un-named	5/9/54	12:27 PM	0.08
Charlie	Ponape	Un-named	5/16/54	11:16 AM	0.1
Able	Rongelap	Rongelap	3/2/54	1:40 PM	1350
Able	Rongelap	Rongelap	¾/54	2:10 PM	2700
Able	Rongelap	Un-named	3/19/54	5:20 PM	140
Able	Rongelap	Arbar	3/19/54	5:20 PM	9
Able	Rongelap	Rongelap	3/19/54	5:22 PM	15
Able	Rongelap	Eniarok	3/19/54	5:24 PM	84
Able	Rongelap	Mellu	3/19/54	5:26 PM	70
Able	Rongelap	Un-named	3/19/54	5:28 PM	70
Able	Rongelap	Rongelap	3/28/54	11:34 AM	28

Table A-l - - continued.

Flight Pattern	Atoll	Island	Local Date	Local Time	mR hr^{-1}
Able	Rongelap	Rongelap	3/31/54	10:22 AM	78
Able	Rongelap	Rongelap	4/8/54	10:33 AM	94
Able	Rongelap	Rongelap	4/12/54	11:09 AM	17.8
Able	Rongelap	Rongelap	4/21/54	10:06 AM	12
Able	Rongelap	Rongelap	4/27/54	10:41 AM	8
Able	Rongelap	Rongelap	5/1/54	8:45 AM	20
Able	Rongelap	Rongelap	5/6/54	10:38 AM	8
Able	Rongelap	Rongelap	5/7/54	10:19 AM	30
Able	Rongelap	Rongelap	5/8/54	9:28 AM	6.5
Able	Rongelap	Rongelap	5/15/54	9:07 AM	5.8
Able	Rongelap	Rongelap	5/16/54	8:36 AM	4.2
Able	Rongerik	Rongerik	3/2/54	2:00 PM	1720
Able	Rongerik	Rongerik	314154	2:20 PM	1050
Able	Rongerik	Bock	3/19/54	5:39 PM	20
Able	Rongerik	Eniwetak	3/19/54	5:41 PM	80
Able	Rongerik	Rongerik	3/19/54	5:43 PM	140
Able	Rongerik	Latoback	3/19/54	5:45 PM	120
Able	Rongerik	Rongerik	3/28/54	1 1:53 AM	36
Able	Rongerik	Rongerik	3/31/54	10:36 AM	58
Able	Rongerik	Rongerik	4/8/54	10:47 AM	82
Able	Rongerik	Rongerik	4/12/54	11:24 AM	18.6
Able	Rongerik	Rongerik	4/21/54	10:20 AM	8
Able	Rongerik	Rongerik	4/27/54	10:55 AM	11
Able	Rongerik	. Rongerik	5/1/54	8:58 AM	8
Able	Rongerik	Rongerik	5/6/54	10:52 AM	3
Able	Rongerik	Rongerik	5/7/54	10:33 AM	22
Able	Rongerik	Rongerik	5/8/54	9:43 AM	4
Able	Rongerik	Rongerik	5/15/54	9:25 AM	5.8
Able	Rongerik	Rongerik	5/16/54	8:54 AM	3
Able	Taka	Taka	3/2/54	4:56 PM	160
Able	Taka	Taka	3/4/54	5:02 PM	44
Able	Taka	Taka	3/28/54	2:38 PM	8
Able	Taka	Taka	3/31/54	1:30 PM	6.8
Able	Taka	Taka	4/8/54	1:38 PM	16
Able	Taka	Taka	4/12/54	2:22 PM	1.9
Able	Taka	Taka	4/21/54	1:04 PM	0.4
Able	T&a	Taka	4/27/54	11:42 PM	2.4
Able	Taka	Taka	5/1/54	11:38 AM	0.7
Able	Taka	Taka	5/6/54	1:40 PM	0.8
Able	Taka	Taka	5/7/54	1:12 PM	5.6
Able	Taka	Taka	5/8/54	12:26 PM	1.5
Able	T&a	Taka	5/15/54	12:08 PM	1

Table A-l - - continued.

Flight Pattern	Atoll	Island	Local Date	Local Time	mR hr^{-1}
Able	Taka	Taka	5/16/54	11:25 AM	0.6
Able	Taongi	Taongi	3/2/54	3:25 PM	1.4
Able	Taongi	Taongi	¾/54	3:33 PM	1.6
Able	Taongi	Sibylla	3/28/54	1:13 PM	1
Able	Taongi	Sibylla	3/31/54	11:58 AM	0.4
Able	Taongi	Sibylla	4/8/54	12:10 PM	0
Able	Taongi	Sibylla	4/12/54	12:47 PM	0.04
Able	Taongi	Sibylla	4/21/54	11:45 AM	0.04
Able	Taongi	Sibylla	4/27/54	12:23 PM	0.2
Able	Taongi	Sibylla	5/1/54	10:14 AM	0.04
Able	Taongi	Sibylla	5/6/54	12:15 PM	0.2
Able	Taongi	Sibylla	5/7/54	11:51 AM	0.2
Able	Taongi	Sibylla	5/8/54	11:11 AM	0
Able	Taongi	Sibylla	5/15/54	10:46 AM	0
Able	Taongi	Sibylla	5/16/54	10:06 AM	0
Able	Ujae	Ujae	3/2/54	12:24 PM	0.1
Able	Ujae	Ujae	¾/54	7:26 AM	0.04
Able	Ujae	Wotya	¾/54	7:34 AM	0.03
Able	Ujae	Ebbetyu	¾/54	7:36 AM	0.04
Able	Ujae	Bock	¾/54	7:44 AM	0.02
Able	Ujae	Enylameg	¾/54	7:52 AM	0.06
Able	Ujae	Wotya	3/19/54	4:19 PM	0.06
Able	Ujae	Ebbetyu	3/19/54	4:25 PM	0.06
Able	Ujae	Enylameg	3/19/54	4:29 PM	0.01
Able	Ujae	Ujae	3/28/54	7:54 AM	0
Able	Ujae	Ujae	3/31/54	8:24 AM	0.2
Able	Ujae	Ujae	4/8/54	9:30 AM	0.3
Able	Ujae	Ujae	4/12/54	9:30 AM	0.02
Able	Uj ae	Ujae	4/21/54	8:34 AM	0
Able	Ujae	Ujae	4/27/54	9:03 AM	0.2
Able	Ujae	Ujae	5/1/54	7:07 AM	0.08
Able	Ujae	Ujae	5/6/54	8:45 AM	0
Able	Ujae	Ujae	5/7/54	8:32 AM	0.8
Able	Ujae	Ujae	5/8/54	7:37 AM	0.2
Able	Ujae	Ujae	5/15/54	7:33 AM	0.08
Able	Ujae	Ujae	5/16/54	6:57 AM	0.06
Charlie	Ujelang	Un-named	3/3/54	8:15 AM	0.8
Charlie	Ujelang	Cn-named	5/2/54	2:50 PM	0.06
Charlie	Ujelang	Un-named	5/9/54	2:02 PM	0
Able	Utirik	Utirik	3/2/54	4:51 PM	240
Able	Utirik	Utirik	¾/54	4:55 PM	48
Able	Utirik	Un-named	3/19/54	7:10 PM	4

Table A-l - - continued.

Flight Pattern	Atoll	Island	Local Date	Local Time	mR hr^{-1}
Able	Utirik	Piji	3/19/54	7:11 PM	12
Able	Utirik	Un-named	3/19/54	7:12 PM	8
Able	Utirik	Utirik	3/19/54	7:13 PM	12
Xble	Utirik	Utirik	3/28/54	2:33 PM	0
Able	Utirik	Utirik	3/31/54	12:20 PM	6.8
Able	Utirik	Utirik	4/8/54	1:32 PM	12
Able	Utirik	Utirik	4/12/54	2:15 PM	3.8
Able	Utirik	Utirik	4/21/54	12:59 PM	0.8
Able	Utirik	Utirik	4/27/54	11:35 PM	2
Xble	Utirik	Utirik	5/1/54	11:35 AM	1.7
Able	Utirik	Utirik	5/6/54	1:35 PM	0.8
Able	Utirik	Utirik	5/7/54	1:18 PM	6
Able	Utirik	Utirik	5/8/54	12:23 PM	1.2
Able	Utirik	Utirik	5/15/54	12:04 PM	1
Able	Utirik	Utirik	5/16/54	11:24 AM	0.8
Able	Wotho	Wotho	3/2/54	1:00 PM	1
Able	Wotho	Kabben	3/4/54	8:14 AM	1.6
Able	Wotho	Wotho	3/4/54	8:19 AM	1.6
Able	wotho	Medyeron	3/4/54	8:20 AM	0.8
Able	Wotho	Kabben	3/19/54	4:43 PM	0.05
Able	Wotho	Wotho	3/19/54	4:48 PM	0.03
Able	wotho	Medyeron	3/19/54	4:49 PM	0.05
Able	Wotho	Wotho	3/28/54	8:29 AM	0
Able	wotho	Wotho	3/31/54	9:10 AM	1.7
Able	Wotho	Wotho	4/8/54	9:56 AM	1.1
Able	wotho	Wotho	4/12/54	9:59 AM	0.2
Able	Wotho	Wotho	4/21/54	9:01 AM	0
Able	wotho	Wotho	4/27/54	9:30 AM	0
Able	Wotho	Wotho	5/1/54	7:37 AM	0.3
Able	Wotho	Wotho	5/6/54	9:12 AM	0.08
Xble	Wotho	Wotho	5/7/54	8:57 AM	1.6
Able	Wotho	Wotho	5/8/54	8:10 AM	0.2
Able	Wotho	Wotho	5/15/54	8:00 AM	0.08
Able	Wotho	Wotho	5/16/54	7:22 AM	0.08
Baker	Wotje	Wotje	3/3/54	8:51 AM	20
Baker	Wotje	Wotje	4/3/54	1:04 PM	1.4
Baker	Wotje	Wotje	4/12/54	2:04 PM	0.8
Baker	Wotje	Wotje	4/21/54	3:59 PM	0.3
Baker	Wotje	Wotje	5/2/54	2:20 PM	0.06
Baker	Wotje	Wotje	5/9/54	1:43 PM	1.7
Baker	Wotje	Wotje	5/16/54	11:15 AM	0.15

Table A-2. Fixed Monitor Data from Operation Castle.

		mR hr^{-1}			
Local Date	Local Time	Rongerik	Majuro	Kwajalein	Ujelang
2/24/54	12:OO PM	0.15	0.13		
2/24/54	6:00 PM				
2125154	12:00 AM				
2/25/54	6:00 AM				
2/25/54	12:00 PM	0.07	0.18		
2/25/54	6:00 PM	0.04	0.07		0.013
2/26/54	12:00 AM	0.03	0.03		0.013
2/26/54	6:00 AM	0.03	0.05		0.012
2/26/54	12:OO PM	0.05	0.13		0.015
2126154	6:00 PM	0.03	0.07		0.013
2/27/54	12:00 AM				0.013
2/27/54	6:00 AM				0.013
2/27/54	12:00 PM	0.04	0.17		0.015
2/27/54	6:00 PM	0.03	0.08		0.015
2/28/54	12:00 AM	0.03	0.05		0.013
2/28/54	6:00 AM	0.03	0.05		0.013
2/28/54	12:00 PM	0.04	0.09		0.015
2/28/54	6:00 PM	0.05	0.07		0.015
3/1/54	12:00 AM				0.015
3/1/54	6:00 AM	0.07	0.05		0.013
3/1/54	12:00 PM	0.05	0.1		0.013
3/1/54	6:00 PM	100	0.1		0.013
3/2/54	12:00 AM	100	0.06		0.28
3/2/54	6:00 AM		0.04		1.5
3/2/54	12:00 PM		0.07		1.2
3/2/54	6:00 PM		0.05	0.06	1
3/3/54	12:00 AM			0.02	
3/3/54	6:00 AM		0.2	0.01	
3/3/54	12:00 PM		1.5	0.3	
3/3/54	6:00 PM		1.5		1
3/4/54	12:00 AM		1	0.06	0.;
3/4/54	6:00 AM		1	0.009	0.5
3/4/54	12:00 PM		1.5	0.5	0.45
3/4/54	6:00 PM		0.9	0.2	0.4
3/5/54	12:OO AM		0.9	0.02	0.3
3/5/54	6:00 AM			0.02	0.25
3/5/54	12:00 PM		0.9	0.45	0.25
3/5/54	6:00 PM				0.2
3/6/54	12:00 AM		0.9	0.01	0.15
3/6/54	6:00 AM		0.9		0.13
3/6/54	12:00 PM		1	0.3	0.13
3/6/54	6:00 PM		0.9	0.3	0.1

Table A-2 - - continued.

		mR hr^{-1}			
Local Date	Local Time	Rongerik	Majuro	Kwajalein	Ujelang
3/7/54	12:00 AM		0.9	0.1	0.1
3/7/54	6:00 AM			0.1	0.1
3/7/54	12:00 PM		1	0.7	0.1
3/7/54	6:00 PM		1	0.5	0.07
3/8/54	12:OO AM		1		0.07
3/8/54	6:00 AM		0.8	0.14	0.05
3/8/54	12:00 PM		1.3	0.8	0.07
3/8/54	6:00 PM		1	0.7	0.05
3/9/54	12:OO AM		1		0.045
3/9/54	6:00 AM		0.8	0.07	0.045
3/9/54	12:OO PM		0.7	0.7	0.06
3/9/54	6:00 PM			0.15	0.05
3/10/54	12:OOAM		0.5	0.1	0.007
3/10/54	6:00 AM		0.5	0.08	0.007
3/10/54	12:OO PM		0.8	0.7	0.008
3/10/54	6:00 PM		0.08	0.3	0.008
3/11/54	12:00 AM			0.15	0.008
3/11/54	6:00 AM			0.1	0.008
3/11/54	12:00 PM		0.1	0.7	0.008
3/11/54	6:00 PM		0.06	0.3	0.008
3/12/54	12:00 AM		0.05	0.05	0.008
3/12/54	6:00 AM		0.06	0.03	0.008
3/12/54	12:OO PM		0.04	0.03	0.008
3/12/54	6:00 PM			0.07	0.03
3/13/54	12:00 AM		0.04	0.08	0.025
3/13/54	6:00 AM		0.02	0.06	0.009
3/13/54	12:00 PM		0.06		0.015
3/13/54	6:00 PM			0.7	0.01
3/14/54	12:00 AM		0.02	0.15	0.3
3/14/54	6:00 AM		0.02	0.07	0.25
3/14/54	12:oo PM		0.06	1.7	0.3
3/14/54	6:00 PM		0.04	0.8	0.25
3/15/54	12:00 AM		0.015	0.15	0.2
3/15/54	6:00 AM		0.01	0.15	0.25
3/15/54	12:00 PM		0.06	1.9	0.25
3/15/54	6:00 PM		0.02	0.08	0.14
3/16/54	13:00 AM		0.01	0.3	0.1
3/16/54	6:00 AM		0.007	0.3	0.05
3/16/54	12:00 PM		0.03	2.7	0.08
3/16/54	6:00 PM		0.02	1.7	0.03
3/17/54	13:00 AM		0.02	0.45	0.02
3/17/54	6:00 AM		0.01	0.3	0.017

Table A-2 - - continued.

		mR hr^{-1}			
Local Date	Local Time	Rongerik	Majuro	Kwajalein	Uj elang
3/17/54	12:00 P M		0.03	3	0.1
3/17/54	6:00 PM		0.009		0.02
3/18/54	12:oo AM		0.003	0.009	0.02
3/18/54	6:00 AM		0.003		0.02
3/18/54	13:oo PM		0.02		0.06
3/18/54	6:00 PM		0.003	0.08	0.02
3/19/54	12:oo AM		0.002	0.08	0.02
3/19/54	6:00 AM		0.002	0.08	0.017
3/19/54	12:oo PM		0.009	0.1	0.035
3/19/54	6:00 PM		0.004	0.06	0.02
3/20/54	12:00 AM		0.002	0.05	0.017
3/20/54	6:00 AM		0.04	0.05	0.02
3/20/54	12:oo PM			0.08	0.03
3/20/54	6:00 PM				0.017
3/21/54	12:00 AM		0.002		0.015
3/21/54	6:00 AM		0.0015	0.004	0.017
3/21/54	12:oo PM		0.04	0.002	0.03
3/21/54	6:00 PM		0.002		0.015
3/22/54	12:oo AM		0.0015	0.05	0.013
3/22/54	6:00 AM			0.05	0.017
3/22/54	12:oo PM		0.015	0.06	0.012
3/22/54	6:00 PM			0.06	0.005
3/23/54	12:oo AM		0.001	0.04	0.004
3/23/54	6:00 AM		0.001	0.04	0.004
3/23/54	12:oo PM			0.08	0.006
3/23/54	6:00 PM		0.001	0.06	0.004
3/24/54	12:00 AM		0.001	0.04	0.004
3/24/54	6:00 AM		0.001	0.04	0.004
3/24/54	12:oo PM		0.009		0.008
3/24/54	6:00 PM			0.05	0.004
3/25/54	12:oo AM			0.04	0.004
3/25/54	6:00 AM			0.04	0.004
3/25/54	12:oo PM				0.005
3/25/54	6:00 PM			0.04	0.004
3/26/54	12:00 AM			0.04	0.004
3/26/54	6:00 AM			0.04	0.004
3/26/54	12:00 PM		0.004	0.1	0.006
3/26/54	6:00 PM		0.001		0.004
3/27/54	12:00 AM		0.001	0.03	0.004
3/27/54	6:00 AM				0.004
3/27/54	12:oo PM		0.002		0.005
3/27/54	6:00 PM		0.001	0.07	0.004

Table A-2 - - continued.

		mR hr^{-1}			
Local Date	Local Time	Rongerik	Majuro	Kwajalein	Uj elang
3/28/54	12:00 AM		0.001	0.03	0.004
3/28/54	6:00 AM		0.001	0.02	0.005
3/28/54	12:00 PM		0.005	0.1	0.04
3/28/54	6:00 PM		0.001	0.04	0.02
3/29/54	12:OO AM			0.02	0.06
3/29/54	6:00 AM		0.001		0.08
3/29/54	12:00 PM		0.004	0.14	0.14
3/29/54	6:00 PM		0.001	0.04	
3/30/54	12:00 AM		0.001	0.01	
3/30/54	6:00 AM		0.001	0.015	
3/30/54	12:00 PM		0.05	0.15	
3/30/54	6:00 PM		0.3	0.7	
3/31/54	12:00 AM		0.7	4	
3/31/54	6:00 AM		1	5.5	
3/31/54	12:00 PM		1.5	6.5	
3/31/54	6:00 PM		1.5	13	
4/1/54	12:00 AM		1.3	20	
4/1/54	6:00 AM		1.3	16	
4/1/54	12:00 PM		1.3	16	
4/1/54	6:00 PM		1.3	16	
4/2/54	12:00 AM		0.001	14	
4/2/54	6:00 AM		1.2	13	
4/2/54	12:00 PM		1.3		
4/2/54	6:00 PM		1	13	
4/3/54	12:00 AM		0.8	11	
4/3/54	6:00 AM		0.8	10	
4/3/54	12:00 PM		0.8	10	
4/3/54	6:00 PM		0.8	6	
4/4/54	12:00 AM		0.7	6	
4/4/54	6:00 AM		0.6		
4/4/54	12:00 PM		0.5	0.001	
4/4/54	6:00 PM				
4/5/54	12:00 AM		0.4		
4/5/54	6:00 AM		0.3		
4/5/54	12:00 PM		0.4		
4/5/54	6:00 PM		0.4		
4/6/54	12:00 AM				
4/6/54	6:00 AM		0.3		
4/6/54	12:00 PM		0.25		
4/6/54	6:00 PM		0.25	0.5	
4/7/54	12:00 AM		0.25	0.8	
4/7/54	6:00 AM			0.7	

Table A-2 - - continued.

		mR hr^{-1}			
Local Date	Local Time	Rongerik	Majuro	Kwajalein	Ujelang
4/7/54	12:OO PM		0.3		
4/7/54	6:00 PM			1	
4/8/54	12:00 AM		0.2	1.3	
4/8/54	6:00 AM		0.2	1	
4/8/54	12:00 PM		0.25	1.2	
4/8/54	6:00 PM		0.2	1.3	0.85
4/9/54	12:00 AM		0.15	1.2	0.95
4/9/54	6:00 AM		0.15	1.3	0.95
4/9/54	12:00 PM		0.2	1.5	0.95
4/9/54	6:00 PM		0.2	1.5	0.95
4/10/54	12:00 AM		0.2	1.3	0.95
4/10/54	6:00 AM		0.15	1.3	0.95
4/10/54	12:00 PM		0.3		0.95
4/10/54	6:00 PM		0.25	1.6	0.95
4/11/54	12:00 AM				0.85
4/11/54	6:00 AM		0.2	1.6	0.85
4/11/54	12:00 PM		0.25	2	0.85
4/11/54	6:00 PM		0.2	1.5	0.85
4/12/54	12:00 AM		0.2	1.5	0.75
4/12/54	6:00 AM		0.25	1.2	0.65
4/12/54	12:OO PM		0.2	1.5	0.75
4/12/54	6:00 PM		0.15	1.5	0.65
4/13/54	12:00 AM		0.15	1.2	
4/13/54	6:00 AM		0.08	1.3	
4/13/54	12:00 PM		0.25	1.5	
4/13/54	6:00 PM		0.2	1.5	
4/14/54	12:00 AM		0.2	1	
4/14/54	6:00 AM		0.2	1	
4/14/54	12:00 PM		0.15	1.3	
4/14/54	6:00 PM		0.08	0.2	
4/15/54	12:oo AM				
4/15/54	6:00 AM			0.15	
4/15/54	12:00 PM		0.25	0.2	
4/15/54	6:00 PM		0.25	0.2	
4/16/54	12:00 AM		0.3	0.15	
4/16/54	6:00 AM				
4/16/54	12:00 PM		0.15	0.15	
4/16/54	6:00 PM		0.05	0.5	
4/17/54	12:00 AM		0.05		
4/17/54	6:00 AM		0.07	0.1	
4/17/54	12:00 PM		0.08	0.1	
4/17/54	6:00 PM		0.15	0.15	

Table A-2 - - continued.

Local Date	Local Time	Rongerik (mR hr⁻¹)	Majuro (mR hr⁻¹)	Kwajalein (mR hr⁻¹)	Ujelang (mR hr⁻¹)
4/18/54	12:00 AM		0.25	0.15	
4/18/54	6:00 AM		0.25	0.1	
4/18/54	12:00 PM		0.4	0.15	
4/18/54	6:00 PM		0.2	0.15	
4/19/54	12:00 AM		0.09	0.1	
4/19/54	6:00 AM		0.1	0.1	
4/19/54	12:00 PM		0.08	0.15	
4/19/54	6:00 PM		0.15	0.15	
4/20/54	12:00 AM		0.06	0.4	
4/20/54	6:00 AM		0.009	0.1	
4/20/54	12:00 PM		0.03	0.15	
4/20/54	6:00 PM		0.002	0.1	
4/21/54	12:00 AM		0.002	0.1	
4/21/54	6:00 AM		0.002	0.09	
4/21/54	12:00 PM		0.08	0.1	0.065
4/21/54	6:00 PM		0.007	0.1	0.065
4/22/54	12:00 AM		0.002	0.08	0.06
4/22/54	6:00 AM		0.002	0.08	0.06
4/22/54	12:00 PM		0.003	0.1	0.065
4/22/54	6:00 PM		0.003	0.1	0.065
4/23/54	12:00 AM		0.003	0.08	0.06
4/23/54	6:00 AM		0.002	0.07	0.06
4/23/54	12:00 PM		0.02	0.1	0.06
4/23/54	6:00 PM		0.001	0.08	0.06
4/24/54	12:00 AM		0.002	0.08	0.06
4/24/54	6:00 AM		0.002	0.08	0.06
4/24/54	12:00 PM		0.004	0.1	0.065
4/24/54	6:00 PM			0.07	0.06
4/25/54	12:00 AM		0.002	0.06	0.06
4/25/54	6:00 AM			0.05	0.06
4/25/54	12:00 PM		0.003	0.07	0.06
4/25/54	6:00 PM		0.001	0.05	0.065
4/26/54	12:00 AM		0.001	0.05	0.06
4/26/54	6:00 AM			0.04	0.05
4/26/54	12:00 PM		0.001	0.06	0.075
4/26/54	6:00 PM		0.002	0.05	0.06
4/27/54	12:00 AM		0.001	0.05	0.45
4/27/54	6:00 AM		0.001		0.55
4/27/54	12:00 PM			0.04	1.3
4/27/54	6:00 PM		0.002	0.04	0.3
4/28/54	12:00 AM		0.002	0.05	0.2
4/28/54	6:00 AM		0.002	0.04	0.2

Table A-2 - - continued.

		mR hr^{-1}			
Local Date	Local Time	Rongerik	Majuro	Kwajalein	Uj elang
4/28/54	12:00 PM		0.15	0.05	0.2
4/28/54	6:00 PM		0.002	0.05	0.2
4/29/54	12:OO AM		0.002	0.06	0.17
4/29/54	6:00 AM			0.06	0.25
4/29/54	12:00 PM		0.03	0.07	0.2
4/29/54	6:00 PM		0.06	0.07	0.15
4/30/54	12:oo AM		0.002	0.08	0.15
4/30/54	6:00 AM		0.001	0.08	0.13
4/30/54	12:oo PM				0.13
4/30/54	6:00 PM		0.002	0.1	0.15
5/1/54	12:oo AM			0.1	0.12
5/1/54	6:00 AM		0.001	0.1	0.12
5/1/54	12:oo PM		0.02	0.1	0.13
5/1/54	6:00 PM		0.002	0.09	0.15
5/2/54	12:oo AM		0.00 1	0.08	0.12
5/2/54	6:00 AM		0.001		0.11
5/2/54	12:00 PM		0.006	0.15	0.12
5/2/54	6:00 PM		0.002	0.1	0.14
5/3/54	12:00 AM		0.002	0.08	0.11
5/3/54	6:00 AM		0.001	0.06	0.1
5/3/54	12:oo PM		0.005	0.08	0.11
5/3/54	6:00 PM		0.002		0.12
5/4/54	12:OO AM		0.001		0.11
5/4/54	6:00 AM		0.001		0.1
5/4/54	12:00 PM				0.11
5/4/54	6:00 PM		0.001	0.04	0.1
5/5/54	12:00 AM		0.001	0.04	0.1
5/5/54	6:00 Aii		0.001		0.1
5/5/54	12:oo PM			0.04	0.11
5/5/54	6:00 PM		0.003	0.1	0.11
5/6/54	12:00 AM		0.002		
5/6/54	6:00 AM		0.002	0.1	7
5/6/54	12:oo PM		0.03	0.1	0.85
5/6/54	6:00 PM		0.1	2	0.65
5/7/54	12:00 AM		0.002	2.5	0.5
5/7/54	6:00 AM		0.001	3	0.5
5/7/54	12:00 PM		0.002	4	0.75
5/7/54	6:00 PM		0.004	4.5	1
5/8/54	12:00 AM		0.004	4	1.5
5/8/54	6:00 AM		0.003	2.7	1.5
5/8/54	12:oo PM		0.01		1
5/8/54	6:00 PM		0.006	3.5	

Table A-2 - - continued.

Local Date	Local Time	mR hr^{-1} Rongerik	Majuro	Kwajalein	Ujelang
5/9/54	12:oo AM		0.001	3.5	
5/9/54	6:00 AM		0.001	3	
5/9/54	12:oo PM		0.006	3	
5/9/54	6:00 PM		0.01	1.3	
5/10/54	12:OO AM			3.3	
5/10/54	6:00 AM		0.01	2.2	
5/10/54	12:00 PM		0.002	0.9	
5/10/54	6:00 PM		0.01	0.8	
5/11/54	12:OO AM		0.002	0.8	
5/11/54	6:00 AM		0.01	0.7	
5/11/54	12:oo PM		0.01	0.7	
5/11/54	6:00 PM		0.006	0.7	
5/12/54	12:00 AM		0.003	0.6	
5/12/54	6:00 AM		0.003	0.6	
5/12/54	12:00 PM		0.02	0.6	
5/12/54	6:00 PM		0.03	0.6	
5/13/54	12:00 AM		0.003	0.5	
5/13/54	6:00 AM		0.004	0.5	
5/13/54	12:oo PM		0.02	0.5	
5/13/54	6:00 PM		0.001	0.5	
5/14/54	12:OOAM		0.01	0.4	
5/14/54	6:00 AM		0.007	0.4	
5/14/54	12:00 PM		0.02	0.4	
5/14/54	6:00 PM		0.06	0.4	
5/15/54	12:00 AM		0.03	0.4	
5/15/54	6:00 AM		0.006	0.4	
5/15/54	12:oo PM		0.007		
5/15/54	6:00 PM		0.02	0.3	
5/16/54	12:OO AM			0.3	
5/16/54	6:00 AM			0.3	
5/16/54	12:00 PM			0.3	

Table A-3. Gummed Film Data for Kwajalein from 1954 to 1958.

Year	Sample day	Count day	Precip Number	dpm ft^{-2} beta 1	beta 2
1954	70	83	6	4969	3785
1954	71	85	4	455	415
1954	72	85	2	478	553
1954	73	87	1	426	420
1954	74	87	1	536	956
1954	75	87	1	367	387
1954	76	87	1	832	657
1954	77	87	2	1182	1668
1954	78	90	5	1013	575
1954	79	90	3	413	407
1954	80	92	1	844	593
1954	81	94	1	897	458
1954	82	93	2	649	672
1954	83	93	5	1620	1170
1954	84	97	3	483	345
1954	85	97	3	103	132
1954	86	96	3	11	82
1954	87	98	5	1366	245
1954	88				
1954	89				
1954	90				
1954	91				
1954	92				
1954	93				
1954	94	103	6	9877	16988
1954	95	106	4	2435	5039
1954	96	107	8	6205	5856
1954	97	106	6	5674	7197
1954	98	111	1	8800	5857
1954	99	108	3	2878	1848
1954	100	108	3	2330	3125
1954	101	112	3	2066	1677
1954	102	117	4	696	898
1954	103	117	1	760	871
1954	104	117	1	1070	788
1954	105	117	3	1315	1020
1954	106	120	3	1116	807
1954	107	120	1	898	633
1954	108	120	1	817	660
1954	109	120	1	353	480
1954	110	120	1	311	313
1954	111	124	3	664	497

Table A-3 - - continued.

Year	Sample day	count day	Precip Number	dpm ft^{-2} beta 1	dpm ft^{-2} beta 2
1954	112	124	2	677	954
1954	113	125	7	779	754
1954	114	125	4	320	211
1954	115	125	4	320	365
1954	116	126	6	408	322
1954	117	126	5	6257	4500
1954	118	131	2	1623	817
1954	119	134	2		
1954	120	135	4	22	38
1954	121	135	1	406	1736
1954	122	134	5	4533	1314
1954	123	136	4	3345	3178
1954	124	135	1	2774	899
1954	125				
1954	126				
1954	127				
1954	128				
1954	129	141	6	16594	10140
1954	130	145	6	2217	2686
1954	131	145	4	2964	3705
1954	132	145	6	2075	2097
1954	133	148	6	1897	2016
1954	134	149	6	42	904
1954	135	147	6	1980	1667
1954	136	148	5	2863	1170
1954	137	150	5	4933	12051
1954	138	148	7	14525	11502
1954	139	148	7	6378	6440
1954	140	159	6	1918	1296
195-F	141	158	3	864	848
1954	142				
1954	143	158	2	690	627
1954	144	159	2	759	527
1953	144	156	4	834	641
1954	145	158	4	600	589
195-i	146	159	7	247	1342
1954	147	158	7	769	660
1954	148	161	6	478	68
1954	149	161	7	394	325
1954	150	161	6	472	392
1954	151	161	6	197	457
1954	152	161	4	408	302

Table A-3 - - continued.

Year	Sample day	Count day	Precip Number	dpm ft^{-2} beta 1	dpm ft^{-2} beta 2
1954	153	166	3	246	2130
1954	15-l	169	5	257	255
1954	155	169	3	259	355
1954	156	169	3	316	306
1954	157	169	1	139	175
1954	158	168	7	471	649
1954	159	168	5	576	345
1954	160	171	5	442	364
1954	161	175	7	440	442
1954	162	173	4	238	312
1954	163	173	1	55	96
1954	164	174	1	302	93
1954	165	178	5	163	154
1954	166	178	2	105	159
1954	167	178	7	360	413
1954	168	181	1	127	96
1954	169	183	6	194	265
1954	170	182	7	181	131
1954	171	182	6	214	269
1954	172				
1954	173	181	1	51	74
1954	174	185	7	512	445
1954	175	187	4	142	97
1954	176	185	7	309	316
1954	177	185	4	161	184
1954	178	189	4	117	124
1954	179	191	7	226	280
1954	180	191	7	132	125
1954	181	191	6	127	136
1954	182			<200	
1954	183			200	
195-F	184			200	
1954	185			200	
1954	186			200	
1954	187			200	
1954	188			200	
1954	189			200	
1954	190			200	
1954	191			200	
1954	193			200	
1954	193			200	
195-i	191			300	

Table A-3 - - continued.

Year	Sample day	Count day	Precip Number	dpm ft^{-2} beta 1	dpm ft^{-2} beta 2
1954	195			200	
1954	196			200	
1954	197			200	
1954	198			200	
1954	199			200	
1954	200			200	
1954	201			200	
1954	202			200	
1954	203			200	
1954	204			200	
1954	205			200	
1954	206			200	
1954	207			200	
1954	208			200	
1954	209			200	
1954	210			200	
1954	211			200	
1954	212			200	
1954	213			<150	
1954	214			150	
1954	215			150	
1954	216			150	
1954	217			150	
1954	218			150	
1954	219			150	
1954	220			150	
1954	221			150	
1954	222			150	
1954	223			150	
1954	224			150	
1954	225			150	
1954	226			150	
1954	227			150	
1954	228			150	
1954	229			150	
1954	230			150	
1954	231			150	
1954	232			150	
1954	233			150	
1954	234	246		229	455
1954	235			<150	
1954	236			150	

Table A-3 - - continued.

Year	Sample day	count day	Precip Number	dpm ft^{-2} beta 1	beta 2
1954	237			150	
1954	238			150	
1954	239			150	
1954	240			150	
1954	241			150	
1954	242			150	
1954	243			150	
1954	244			<100	
1954	245			100	
1954	246			100	
1954	247			100	
1954	248			100	
1954	249			100	
1954	250			100	
1954	251			100	
1953	252			100	
1954	253			100	
1954	254			100	
1954	255			100	
1956	122	204	1	na	
1956	123	204	1	11	
1956	124	204	5	12	
1956	125	204	1	9	
1956	126			na	
1956	127	204	6	27	
1956	128	204	3	18	
1956	129	304	5		
1956	130	204	7	33	
1956	131	204	4	26	
1956	132	204	1	7	
1956	133	204	1	26	
1956	134	204	7	30	
1956	135	204	4	29	
1956	136	204	7	30	
1956	137	304	5	3	
1956	138	204	4	42	
1956	139				
1956	140				
1956	141				
1956	142				
1956	143				
1956	144	208	5	3435	

Table A-3 - - continued.

Year	Sample day	Count day	Precip Number	dpm ft^{-2} beta 1	beta 2
1956	145	204	2	173	
1956	146	204	3	60	
1956	147	204	2	24	
1956	148				
1956	149				
1956	150	204	2	6645	
1956	151	204	5	3762	
1956	152	204	4	1510	
1956	153	251	4	602	
1956	154	251	7	574	
1956	155	251	3	828	
1956	156	251	4	381	
1956	157	251	5	444	
1956	158	251	4	666	
1956	159	251	7	621	
1956	160	251	4	304	
1956	161	251	3	187	
1956	162	251	4	200	
1956	163	251	6	452	
1956	164	251	3	230	
1956	165				
1956	166				
1956	167	251	1	5028	
1956	168	251	4	1910	
1956	169	251	2	6482	
1956	170	251	3	2312	
1956	171	251	6	4647	
1956	172	251	6	2056	
1956	173	251	5	1163	
1956	174	251	4	737	
1956	175	251	4	1921	
1956	176	251	5	3459	
1956	177	251	7	899	
1956	178	251	7	1182	1376
1956	179	251	5	653	
1956	180	251	6	967	
1956	181	251	4	1613	
1956	182	251	5	1203	
1956	183	356	6	173	
1956	184	356	6	605	
1956	185	356	5	655	
1956	186	356	5	504	

Table A-3 - - continued.

Year	Sample day	count day	Precip Number	dpm ft^{-2} beta 1	dpm ft^{-2} beta 2
1956	187	356	4	157	
1956	188	356	3	144	
1956	189	356	5	218	
1956	190	356	3	1216	
1956	191	356	3	170	
1956	192	356	6	652	
1956	193	356	6	433	
1956	194	356	5	285	
1956	195	356	4	131	
1956	196	356	1	381	
1956	197	356	6	922	
1956	198	356	5	841	
1956	199	356	6	533	
1956	200	356	3	189	
1956	201	356	1	157	
1956	202	356	4	125	
1956	203	356	7	181	
1956	204	356	4	58	
1956	205	356	4	107	
1956	206	356	4	71	
1956	207	356	4	89	
1956	208	356	1	78	
1956	209	356	3	216	
1956	210	356	5	190	
1956	211	356	6	125	
1956	213	356	1	89	
1956	213	385	3	78	
1956	214	385	6	106	
1956	215	385	6	73	
1956	216	385	6	141	
1956	217	385	6	133	
1956	218				
1956	219				
1956	220	385	5	199	
1956	221	385	7	107	
1956	222	385	4	74	
1956	223	385	3	46	
1956	224	385	4	78	
1956	225	385	6	97	
1956	226	385	6	82	
1956	227	385	5	58	
1956	228	385	2	37	

Table A-3 - - continued.

Year	Sample day	count day	Precip Number	dpm ft^{-2}	
				beta 1	beta 2
1956	229	385	2	56	
1956	230	385	6	73	
1956	231	385	1	45	
1956	232	385	1	60	
1956	233	385	6	76	
1956	234	385	6	80	
1956	235	385	1	72	
1956	236	385	1	42	
1956	237	385	na		
1956	238	385	6	62	
1956	239	385	6	119	
1956	240	385	6	97	
1956	241	385	6	62	
1956	242	385	4	62	
1956	243	385	4	86	
1956	244	385	5	66	
1956	245	408	7	27	
1956	246	108	1	22	
1956	247	308	1	38	
1956	248	408	1	25	
1956	249	408	7	34	
1956	250	408	1	16	
1956	251	408	5	36	
1956	252	408	6	27	
1956	253	408	4	27	
1956	254	408	6	51	
1956	255	408	5	17	
1956	256	408	3	86	
1956	257	408	6	57	
1956	258	408	6	185	
1956	259	434	2	30	
1956	260	434	7	37	
1956	261				
1956	362	408	2	50	
1956	263	408	4	35	
1956	264	408	4	20	
1956	265	408	6	6	
1956	266	408	1	23	
1956	267	408	3	31	
1956	268	408	6	30	
1956	769	408	6	20	
1956	270	408	5	47	

Table A-2 - - continued.

Year	Sample day	count day	Precip Number	dpm ft^{-2} beta 1	beta 2
1956	271	408	3	20	
1956	272	408	1	6	
1956	273	408	6	21	
1956	274	408	7	38	
1958	121	137		5	
1958	122	137		6	
1958	123	136		21	
1958	124	136	5	44	
1958	125	143	3	14	
1958	126	143	1	15	
1958	127	143	5	21	
1958	128	143	1	1528	
1958	129	144	4	7	
1958	130	144	0	20	
1958	131	144	6	8	
1958	132	147	1	18180	
1958	133	147	1	3404	
1958	134	147	1	8685	
1958	135				
1958	136	156	1	33	
1958	137	155	1	3 5400	
1958	138	156	3	9066	
1958	139	155	2	4258	
1958	140	192	2	1447	
1958	141	155	5	5454	
1958	142	191	2	66	
1958	143	192	2	166	
1958	144	192	2	167	
1958	145	192	2	1069	
1958	146	192	1	147	
1958	147	175	1	506	
1958	148	175	1	399	
1958	149	175	1	4291	
1958	150	175	2	336	
1958	151	175	3	298	
1958	152	188	6	543	
1958	153	188	6	355	
1958	154	184	5	162	
1958	155	176	1	40	
1958	156	176	4	128	
1958	157	176	1	24	
1958	158	176	3	118	

Table A-3 - - continued.

Year	Sample day	Count day	Precip Number	dpm ft^{-2}	
				beta 1	beta 2
1958	159	176	6	479	
1958	160	176	7	12	
1958	161	176	2	380	
1958	162	176	1	34	
1958	163	176	5	1068	
1958	164	185	4	455	
1958	165	184	5	378	
1958	166	184	6	107	
1958	167	184	7	246	
1958	168	184	5	130	
1958	169	184	4	132	
1958	170	183	2	46	
1958	171	184	1	52	
1958	172	184	6	826	
1958	173	185	4	1651	
1958	174	185	4	834	
1958	175	190	5	73	
1958	176	191	1	93	
1958	177	191	7	373	
1958	178	191	1	211	
1958	179	197	4	122	
1958	180	197	4	111	
1958	181	197	4	131	
1958	182	196	5	1323	
1958	183	196	6	2647	
1958	184	197	5	114	
1958	185	200	6	189	
1958	186	203	4	189	
1958	187	206	1	3275	
1958	188	206	1	1098	
1958	189	206	3	563	
1958	190	206	7	1476	
1958	191	206	5	206	
1958	192	206	7	259	
1958	193	206	4	109	
1958	194	218	5	111	
1958	195	218	7	471	
1958	196				
1958	197	218	5	135	
1958	198				
1958	199	218	3	2891	
1958	200	220	6	5228	

Table A-3 - - continued.

Year	Sample day	count day	Precip Number	dpm ft^{-2} beta 1	beta 2
1958	201	218	6	359	
1958	202	220	6	118	
1958	203	234	2	147	
1958	204	234	2	149	
1958	205	234	6	127	
1958	306	234	6	181	
1958	207	234	6	271	
1958	308	234	3	136	
1958	209	234	5	66	
1958	210	234	5	196	
1958	211	234	6	315	
1958	212	234	2	949	
1958	213	248	2	52	
1958	21-I	248	1	41	
1958	215	248	1	42	
1958	216	333	6	352	
1958	317	233	4	149	
1958	218	233	6	308	
1958	219	233	4	420	
1958	220	233	6	428	
1958	221	233	5	350	
1958	333	233	4	466	381
1958	223	233	5	319	
1958	224	261	4	127	
1958	225	260	6	116	
1958	226	260	4	92	
1958	327	260	1	52	
1958	228	261	6	93	
1958	229	261	6	223	
1958	230	260	5	58	
1958	231	255	4	57	
1958	232	255	2	62	
1958	233	255	4	71	
1958	234	255	1	6	
1958	235	255	5	135	
1958	236	255	6	92	
1958	337	255	7	124	
1958	338	255	1	25	
1958	239	255	1	14	
1958	340	256	4	140	
1958	241	356	3	263	
1958	342	256	6	62	

Table A-3 - - continued.

Year	Sample day	count day	Precip Number	dpm ft^{-2} beta 1	beta 2
1958	243	-256	6	135	
1958	244				
1958	245	305		11	
1958	246	310	5	23	
1958	247	310	3	17	
1958	248	310	3	64	
1958	249	310	2	38	
1958	250				
1958	251	301	4	82	
1958	252	301	3	8	
1958	253				
1958	254	301	1	*20*	
1958	255	301	0		
1958	256				
1958	237				
1958	258	301	6	75	
1958	259	297	3	10	
1958	260	305	2	4	
1958	261	303	0	26	
1958	262	303	0	10	
1958	263	305	7	256	
1958	264	305	1	17	
1958	265	305	1	31	
1958	266				
1958	267				
1958	268				
1958	269				
1958	270				
1958	271				
1958	272				
1958	273				
1958	274	317	1	58	
1958	275	319	7	549	
1958	276	319	1	1	
1958	277	319	1	18	
1958	278	319	1	16	
1958	279	319	6	65	
1958	280				
1958	281	325	1	91	
1958	282	325	3	43	

Table A-4. Daily Average Exposure Rates during Operation Redwing

	mR hr^{-1}			
Date	Uj elang	Utirik	Wotho	Rongerik
4126156	0.01	0.02	0.01	0.1
5129156	0.05	0.03	0.2	0.15
5/30/56	0.25	0.03	4.5	0.3
5/31/56	0.26	0.26	0.26	0.26
6/1/56	0.23	0.03	1	3
6/2/56	0.15	0.03	0.85	3
6/3/56	0.13	0.02	0.75	3
6/4/56		0.02		2
6/5/56	0.1	0.02	0.5	2
6/6/56	0.1	0.02	0.4	2
6/7/56	0.07	0.03	0.3	2
6/8/56				1.5
6/9/56				1
6/10/56				1
6/11/56				1
6/12/56	0.07	0.02	0.2	1
6/13/56	0.1	0.02	0.18	1
6/14/56	0.07	0.02	0.48	2
6/15/56	0.15	0.02	0.9	1.5
6/16/56	0.1	0.04	0.8	1
6/17/56	0.07	0.03	0.7	1
6/18/56	0.07	0.04	0.6	1
6/19/56	0.07	0.04	0.7	1
6/20/56	0.07	0.03	0.6	1
6/21/56	0.07	0.02	0.5	1
6/22/56	0.07	0.02	0.5	1
6/23/56	0.08	0.03	0.4	1
6/24/56	0.08	0.03	0.4	0.75
6/25/56	0.08	0.03	0.3	0.5
6/26/56	0.07	0.02	0.3	0.5
6/27/56	0.07	0.02	0.25	0.1
6/28/56	0.07	0.06	0.25	0.1
6/29/56	0.05	0.15	0.23	0.1
6/30/56	0.06	0.15	0.23	0.1
7/1/56	0.05	0.15	0.21	0.1
7/2/56	0.06	0.1 1	0.21	0.1
7/3/56	0.05	0.11	0.19	0.1
7/4/56	0.05	0.1	0.18	0.1
7/5/56	0.05	0.1	0.18	0.1
7/6/56	0.05	0.08	0.18	0.1
7/7/56	0.06	0.08	0.15	0.1
718156	0.05	0.07	0.14	0.1

Table A-4 - - continued.

Date	mR hr^{-1} Ujelang	Utirik	Wotho	Rongerik
7/9/56	**0.04**	**0.07**	0.14	0.1
7/10/56	0.04	0.05	0.11	0.1
7/11/56	0.05	0.06	0.11	0.1
7/12/56	0.05	0.05	0.12	0.1
7/13/56	0.05	0.05	0.1	0.1
7/14/56	0.045	0.04	0.1	0.1
7/15/56	0.045	0.045	0.1	0.1
7/16/56	0.05	0.05	0.09	0.1
7/17/56	0.05	0.04	0.08	0.1
7/18/56	0.04	0.05	0.08	0.1
7/19/56	0.04	0.04	0.08	0.1
7/20/56	0.04	0.04	0.08	0.1
7/21/56	0.04	0.04	0.08	0.1
7/22/56	0.6	0.04	0.08	0.1
7/23/56	1.5			0.1

Table A-5. Daily Average Exposure Rates During Operation Hardtack I.

	mR hr^{-1}			
Date	Utirik	Ujelang	wotho	Rongelap
4/11/58	0.01	0.02	0.02	0.02
5/6/58	0.01	0.2	0.02	0.02
5/7/58	0.01	0.25	0.02	0.02
5/8/58	0.01	0.18	0.02	0.02
5/9/58	0.01	0.15	0.02	0.02
5/10/58	0.01	0.15	0.02	0.02
5/11/58	0.01	0.13	0.02	0.02
5/12/58	0.01	0.09	0.02	0.02
5/13/58	0.13	0.08	0.02	0.02
5/14/58	1	0.22	0.02	1.1
5/15/58	0.8	0.3	0.16	1.2
5/16/58	0.75	0.27	0.23	0.9
5/17/58	0.45	0.25	0.2	0.7
5/18158	0.4	0.22	0.18	0.5
5119158	0.35	0.21	0.14	0.35
5/20/58	0.3	0.2	0.11	0.27
5/21/58	0.28	0.2	0.06	0.25
5/22/58	0.22	0.17	0.05	0.22
5/23/58	0.2	0.17	0.05	0.18
5/24/58	0.19	0.15	0.04	0.17
5/25/58	0.18	0.15	0.04	0.16
5/26/58	0.17	0.12	0.03	0.15
5/27/58	0.17	0.12	0.03	0.14
5/28/58	0.1	0.12	0.03	0.13
5/29/58	0.1	0.12	0.03	0.12
5130158	0.1	0.11	0.05	0.12
5/31/58	0.13	0.11	0.05	0.14
6/1/58	0.11	0.1	0.05	0.13
6/2/58	0.1	0.1	0.05	0.12
6/3/58	0.1	0.1	0.03	0.11
6/4/58	0.1	0.1	0.03	0.09
6/5/58	0.1	0.1	0.03	0.09
6/6/58	0.12	0.1	0.03	0.09
6/7/58	0.13	0.1	0.03	0.08
6/8/58	0.18	0.07	0.03	0.08
6/9/58	0.12	0.07	0.03	0.08
6/10/58	0.12	0.07	0.03	0.08
6/11/58	0.1	0.08	0.03	0.07
6/12/58	0.06	0.06	0.02	0.07
6/13/58	0.07	0.07	0.02	0.07
6/14/58	0.06	0.09	0.02	0.07
6/15/58	0.06	0.08	0.02	0.07

Table A-5 - - continued.

Date	mR hr^{-1}			
	Utirik	Ujelang	Wotho	Rongelap
6/16/58	0.06	0.08	0.02	0.07
6/17/58	0.05	0.07	0.02	0.06
6/18/58	0.04	0.06	0.02	0.06
6119158	0.03	0.05	0.02	0.06
6/20/58	0.05	0.06	0.02	0.06
6/21/58	0.05	0.06	0.02	0.06
6/22/58	0.04	0.06	0.02	0.06
6/23/58	0.04	0.06	0.02	0.06
6/24/58	0.05	0.06	0.02	0.06
6/25/58	0.05	0.04	0.02	0.05
6/26/58	0.05	0.05	0.02	0.05
6/27/58	0.05	0.05	0.02	0.05
6/28/58	0.04	0.05	0.02	0.05
6/29/58	0.04	0.05	0.02	0.06
6/30/58	0.04	0.25	0.02	0.05
7/1/58	0.04	0.18	0.02	0.05
7/2/58	0.04	0.13	0.02	0.07
7/3/58	0.04	0.13	1	0.4
7/4/58	0.04	0.18	0.6	0.25
7/5/58	0.04	0.13	0.4	0.18
7/6/58	0.04	0.12	0.24	0.13
7/7/58	0.04	0.12	0.13	0.1
7/8/58	0.04	0.11	0.11	0.1
7/9/58	0.04	0.1	0.1	0.1
7/10/58	0.04	0.09	0.09	0.08
7/11/58	0.04	0.09	0.09	0.08
7/12/58	0.04	0.08	0.08	0.07
7/13/58	0.04	0.08	0.08	0.07
7/14/58	0.04	0.07	0.05	0.07
7/15/58	0.04	0.07	0.05	0.04
7/16/58	0.05	0.06	0.04	0.04
7/17/58	0.07	0.06	0.06	0.04
7/18/58	0.05	0.06	0.09	0.04
7/19/58	0.05	0.06	0.08	0.04
7/20/58	0.05	0.06	0.08	0.04
7/21/58	0.05	0.06	0.08	0.04
7/22/58	0.06	0.05	0.07	0.04
7/23/58	0.06	0.06	0.07	0.04
7/24/58	0.04	0.05	0.06	0.04
7/25/58	0.04	0.06	0.06	0.04
7/26/58	0.04	0.06	0.07	0.04
7/27/58	0.05	0.06	0.06	0.04

Table A-5 - - continued.

Date	mR hr^{-1}			
	Utirik	Ujelang	wotho	Rongelap
7/28/58	0.06		0.06	0.04
7/29/58	0.04	0.05	0.06	0.04
7/30/58		0.05	0.05	0.04
7/31/58		0.05	0.05	0.04

BIOGRAPHICAL SKETCH

Robert C. Whitcomb. Jr. is a Physical Scientist at the Centers for Disease Control and Prevention (CDC), National Center for Environmental Health (NCEH). His main activities involve dosimetry aspects of Dose Reconstruction projects undertaken by CDC.

Mr. Whitcomb attended Florida Southern College in Lakeland, Florida where he received his Bachelor of Science in Biology in 1982. He later attended the University of Florida in Gainesville, Florida where he received his Master of Science in Environmental Engineering Sciences (Health Physics) in 1987.

Mr. Whitcomb has had broad experience in environmental monitoring programs at sites operated for the Department of Energy, Nuclear Regulatory Commission, and State licensed facilities, including pre-operational monitoring for a proposed Low Level Radioactive Waste (LLRW) site and surveillance of an existing LLRW / Hazardous Waste facility. Other monitoring locations include formerly utilized sites of the Manhattan Project and sites where man's activities have produced Technologically Enhanced Natural Radioactivity. Mr. Whitcomb also has provided considerable environmental health physics expertise for emergency response exercises and training for radiological and hazardous material incident response.

Mr. Whitcomb is a reviewer for the Health Physics Journal and participates in committees concerned with environmental radioactivity. He lives in Suwanee, Georgia with his wife and son.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate. in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

W. Emmett Bolch. Jr., Chair
Professor of Environmental Engineering Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Wesley Bolch
Associate Professor of Nuclear and Radiological Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

David Hinteniang
Associate Professor of Nuclear and Radiological Engineering

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William S. Properzio
Associate Professor of Environmental Engineering Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate. in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Charles W. Miller. Chief
Environmental Dosimetry Section,
Radiation Studies Branch,
National Center for Environmental
Health, Centers for Disease Control
and Prevention

This dissertation was submitted to the Graduate Faculty of the College of Engineering and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

May 2000

M. Jack Ohanian
Dean, College of Engineering

Winfred M. Phillips
Dean. Graduate School